

Frontiers of VR I

Cinematic VR, spatial sound, and the vestibular system



Gordon Wetzstein
Stanford University

EE 267 Virtual Reality

Lecture 13

stanford.edu/class/ee267/

Panoramic Imaging and Cinematic VR

Jaunt VR



Jaunt VR

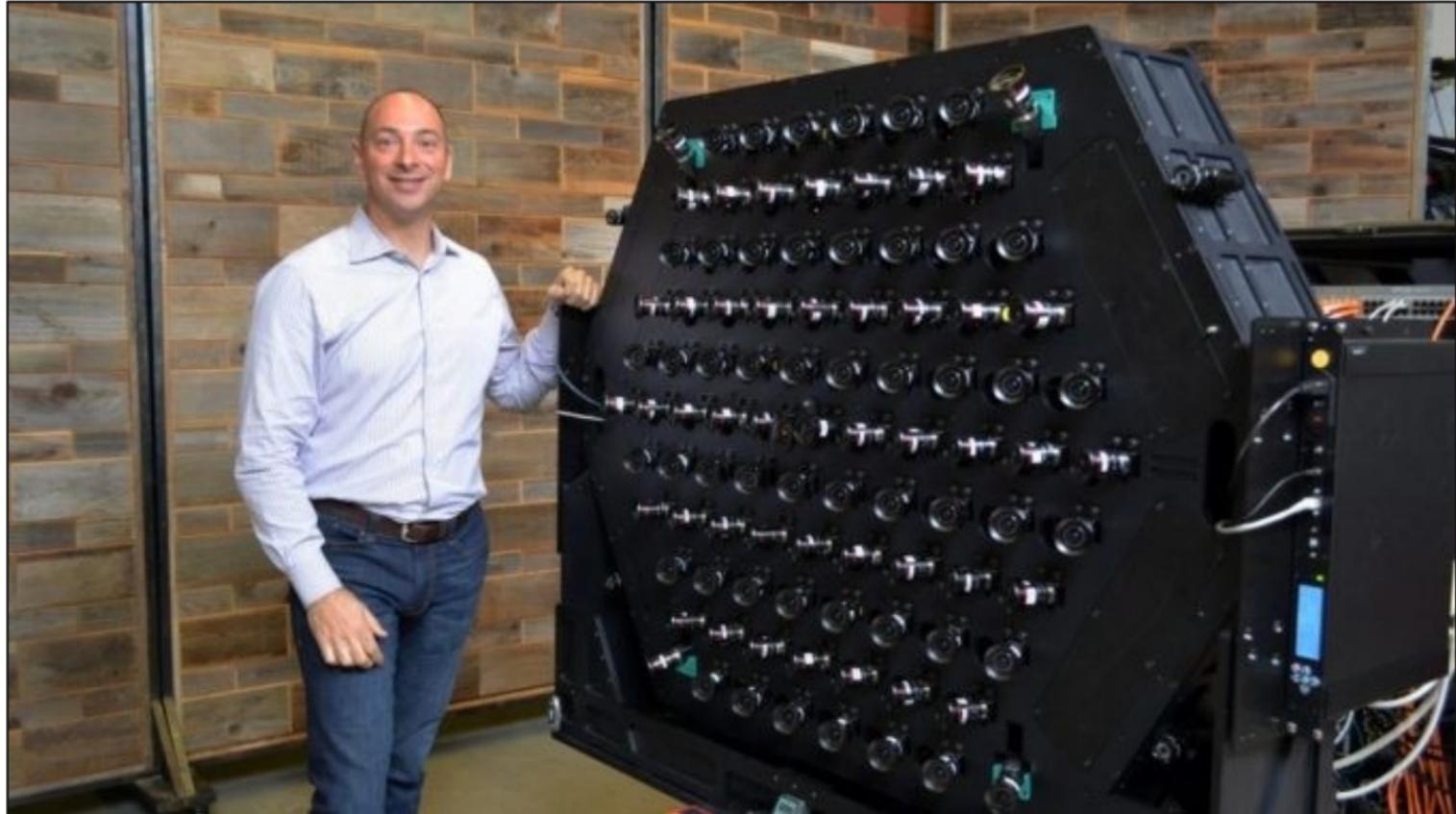




Lytro



Lytro



Google



Nokia

W: 168,36mm / 6.7"



L: 262,95mm / 10.4"



W: 157,83mm / 6.3"

H: 262,95mm / 10.4"

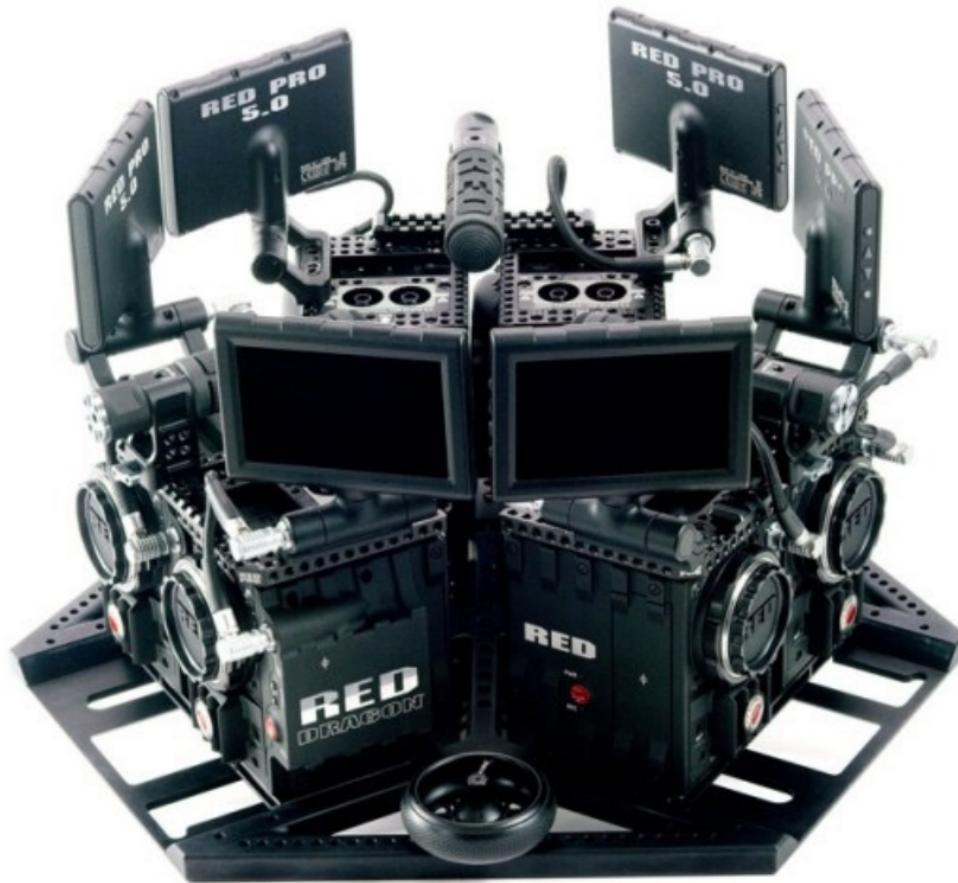
Facebook



see Brian Cabral's SCIEN talk @ talks.stanford.edu



Red



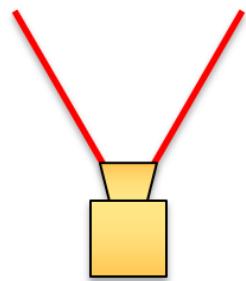
Samsung



Panorama v Stereo Movie v Stereo Panorama

Panorama

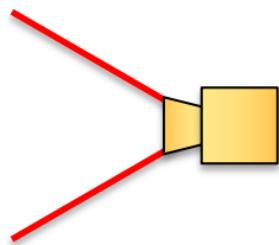
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

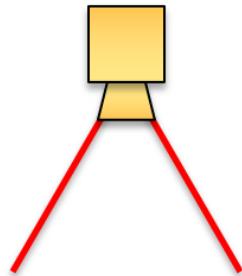
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

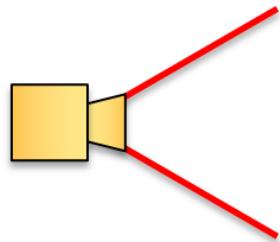
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

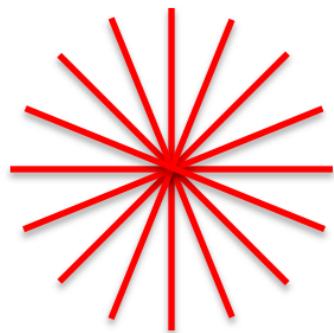
mono & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation

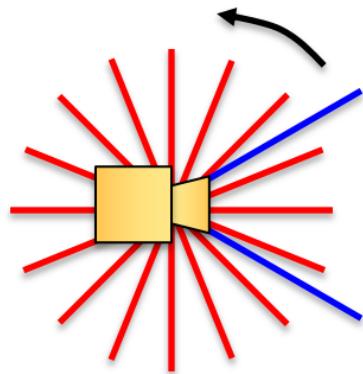


1 center of
projection!

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation

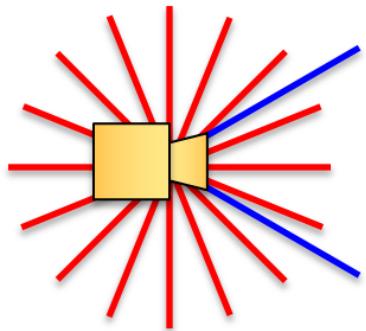


1 center of
projection!

Panorama v Stereo Movie v Stereo Panorama

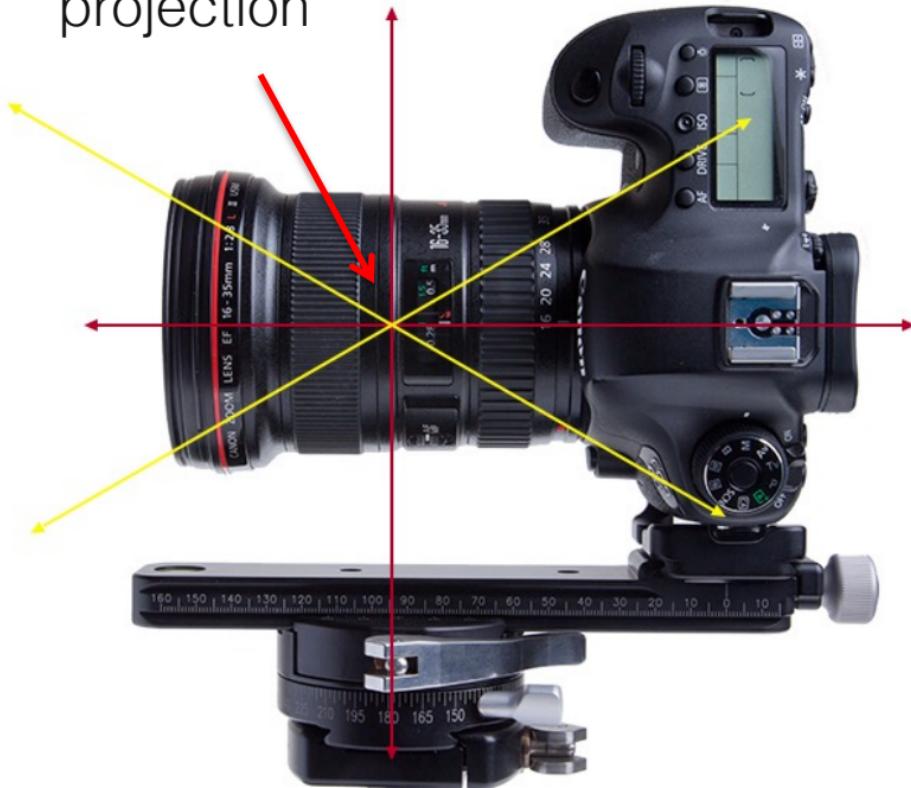
Panorama

mono & head rotation



1 center of
projection!

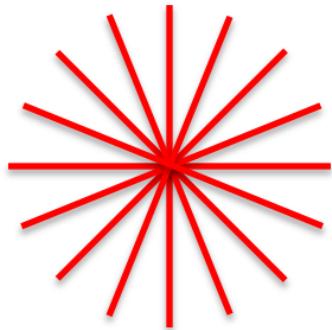
center of
projection



Panorama v Stereo Movie v Stereo Panorama

Panorama

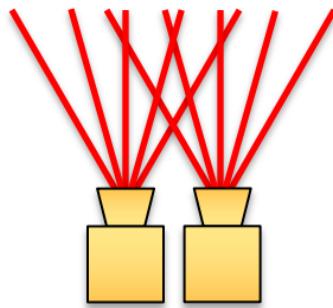
mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



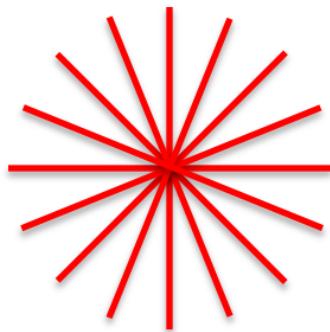
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

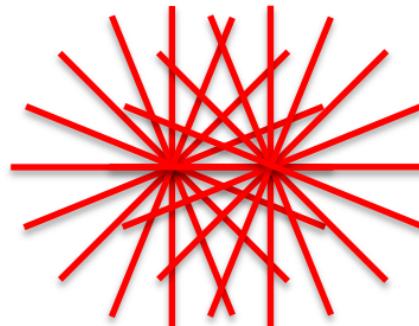
mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



2 centers of
projection!

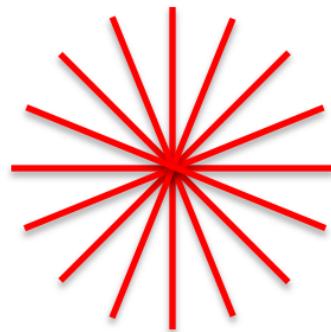
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



2 centers of
projection!

Stereo Panorama

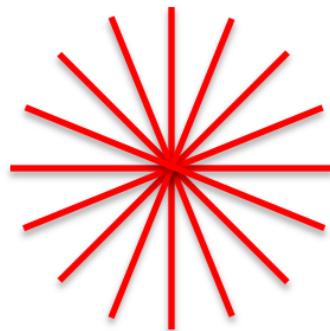
stereo & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



2 centers of
projection!

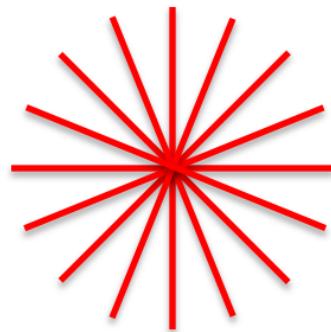
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



2 centers of
projection!

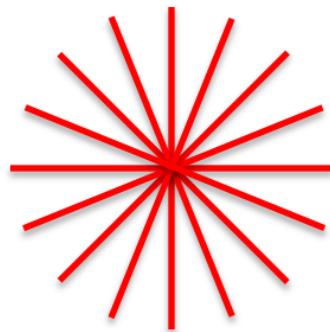
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation



1 center of
projection!

Stereo

stereo & no head rotation



2 centers of
projection!

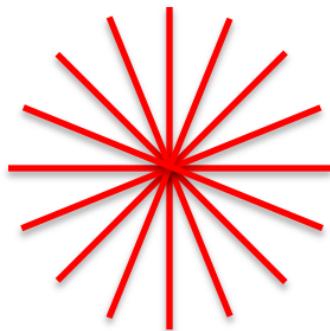
Stereo Panorama

stereo & head rotation

Panorama v Stereo Movie v Stereo Panorama

Panorama

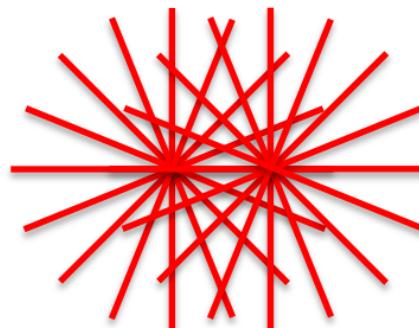
mono & head rotation



1 center of
projection!

Stereo

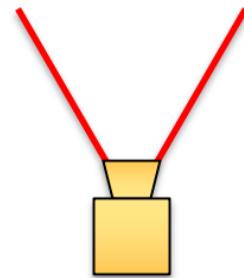
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

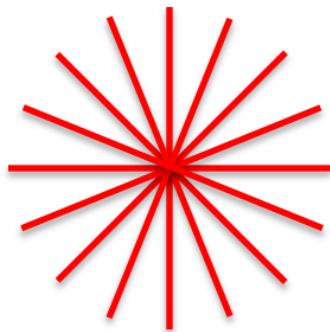
stereo & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

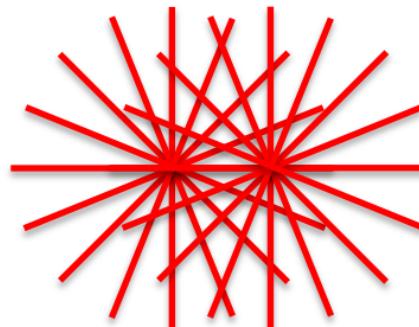
mono & head rotation



1 center of
projection!

Stereo

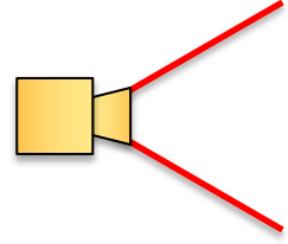
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

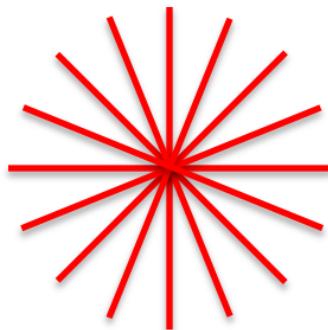
stereo & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

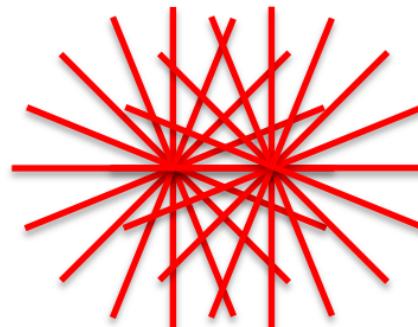
mono & head rotation



1 center of
projection!

Stereo

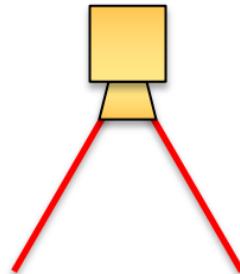
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

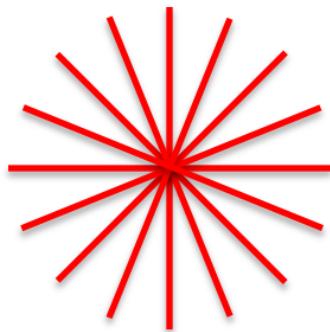
stereo & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

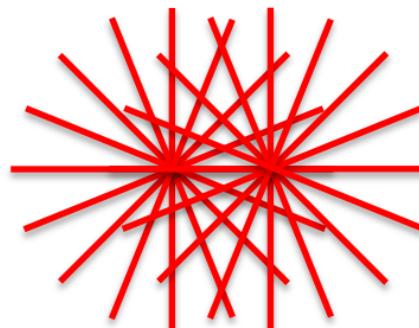
mono & head rotation



1 center of
projection!

Stereo

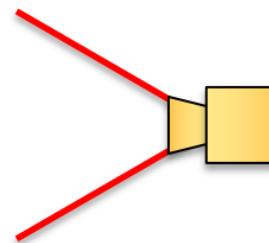
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

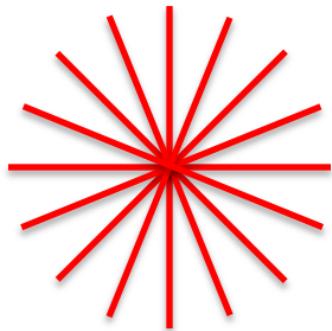
stereo & head rotation



Panorama v Stereo Movie v Stereo Panorama

Panorama

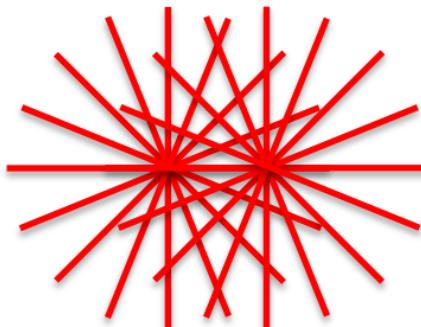
mono & head rotation



1 center of
projection!

Stereo

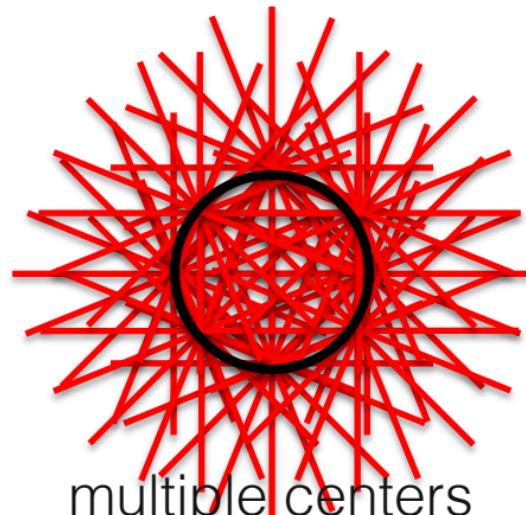
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

stereo & head rotation

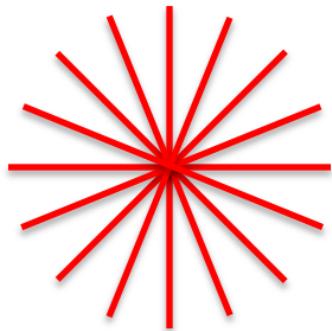


multiple
centers
of projection

Panorama v Stereo Movie v Stereo Panorama

Panorama

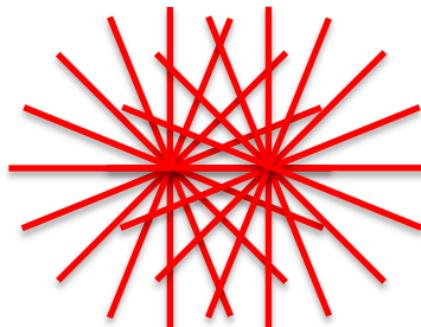
mono & head rotation



1 center of
projection!

Stereo

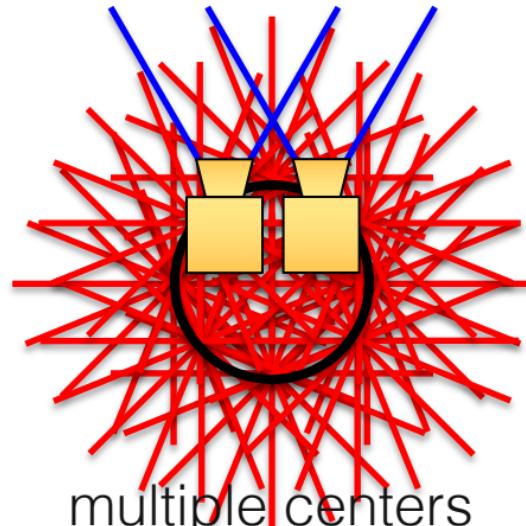
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

stereo & head rotation

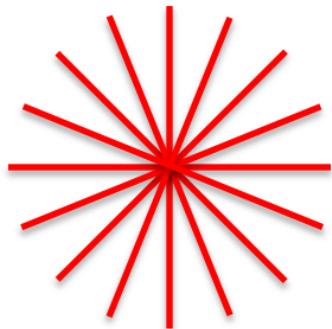


multiple
centers
of projection

Panorama v Stereo Movie v Stereo Panorama

Panorama

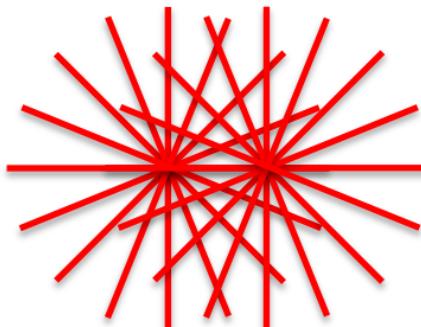
mono & head rotation



1 center of
projection!

Stereo

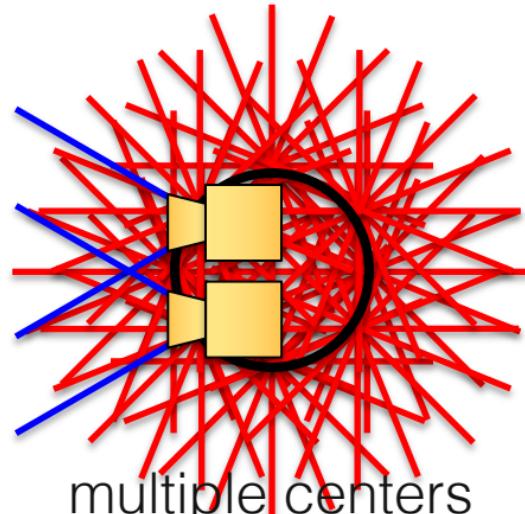
stereo & no head rotation



2 centers of
projection!

Stereo Panorama

stereo & head rotation



multiple
centers
of projection

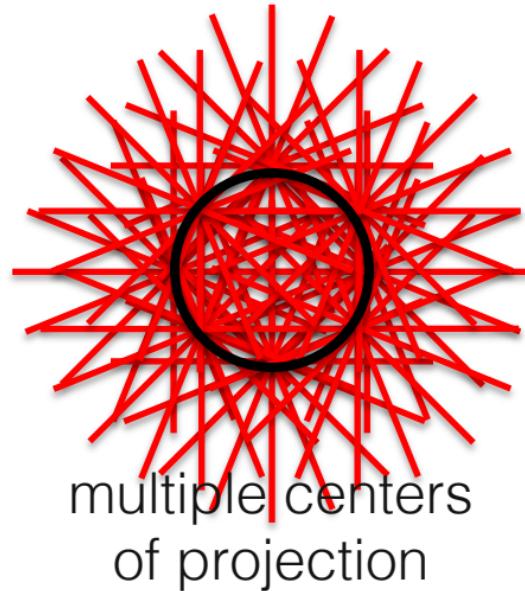
Panorama v Stereo Movie v Stereo Panorama



Light Field!

Stereo Panorama

stereo & head rotation



multiple centers
of projection

Panorama v Stereo Movie v Stereo Panorama

Panorama

mono & head rotation

Ricoh Theta



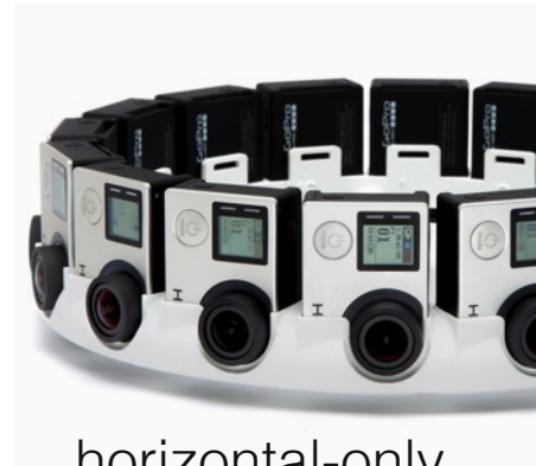
Stereo

stereo & no head rotation



Stereo Panorama

stereo & head rotation



horizontal-only
parallax

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Stitching images together to make a mosaic



Panoramas

Slides from Marc Levoy's excellent CS 178 course

What kind of transformation do we need?



translation?



rotation?



perspective!

Panoramas

Slides from Marc Levoy's excellent CS 178 course

24



- ◆ step 1: find corresponding features in a pair of images
- ◆ step 2: compute perspective from 2nd to 1st image
- ◆ step 3: warp 2nd image so it overlays 1st image
- ◆ step 4: blend images where they overlap one another
- ◆ repeat for 3rd image and mosaic of first two, etc.

© Marc Levoy

Panoramas

Slides from Marc Levoy's excellent CS 178 course

24



- ◆ step 1: find corresponding features in a pair of images
- ◆ step 2: compute perspective from 2nd to 1st image
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- ◆ repeat for 3rd image and mosaic of first two, etc.

take CS 131, EE
368, EE 367!

©Marc Levoy

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Example: the Matterhorn



common
picture
plane of
mosaic
image

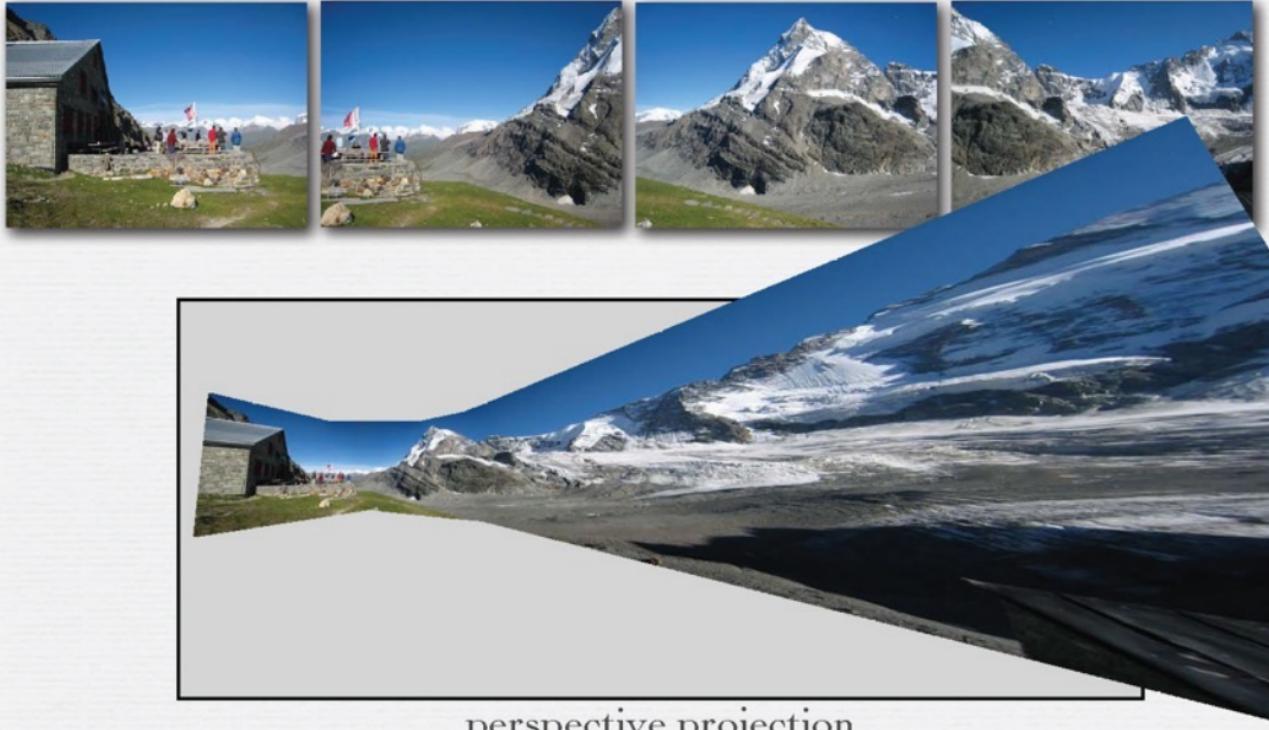


perspective projection

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Using 4 shots instead of 3



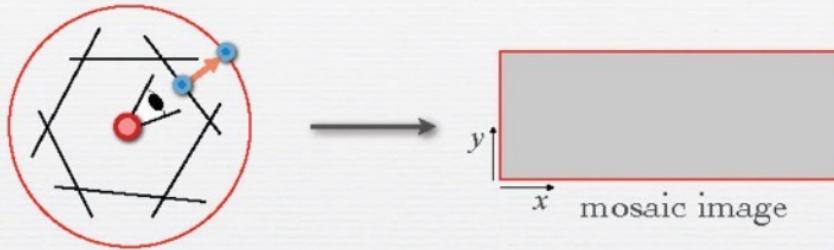
perspective projection

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Cylindrical panoramas

- ♦ even works for 360° panorama



- ♦ project each image onto a cylinder
- ♦ a cylindrical image can be stored as a rectangular image

Panoramas

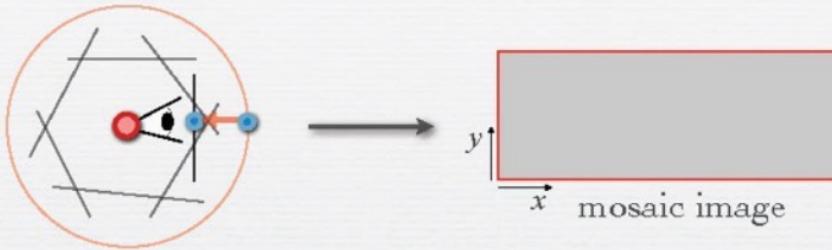
Slides from Marc Levoy's excellent CS 178 course

Cylindrical panoramas

(FLASH DEMO)

<http://graphics.stanford.edu/courses/cs178/applets/projection.html>

- ♦ even works for 360° panorama



- ♦ project each image onto a cylinder
- ♦ a cylindrical image can be stored as a rectangular image
- ♦ to view without distortion, reproject part of the cylinder onto a picture plane representing the display screen
 - if your FOV is narrow, this view won't be too distorted

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Back to the Matterhorn



cylindrical projection

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Back to the Matterhorn



blended

Panoramas

Slides from Marc Levoy's excellent CS 178 course

Spherical panoramas



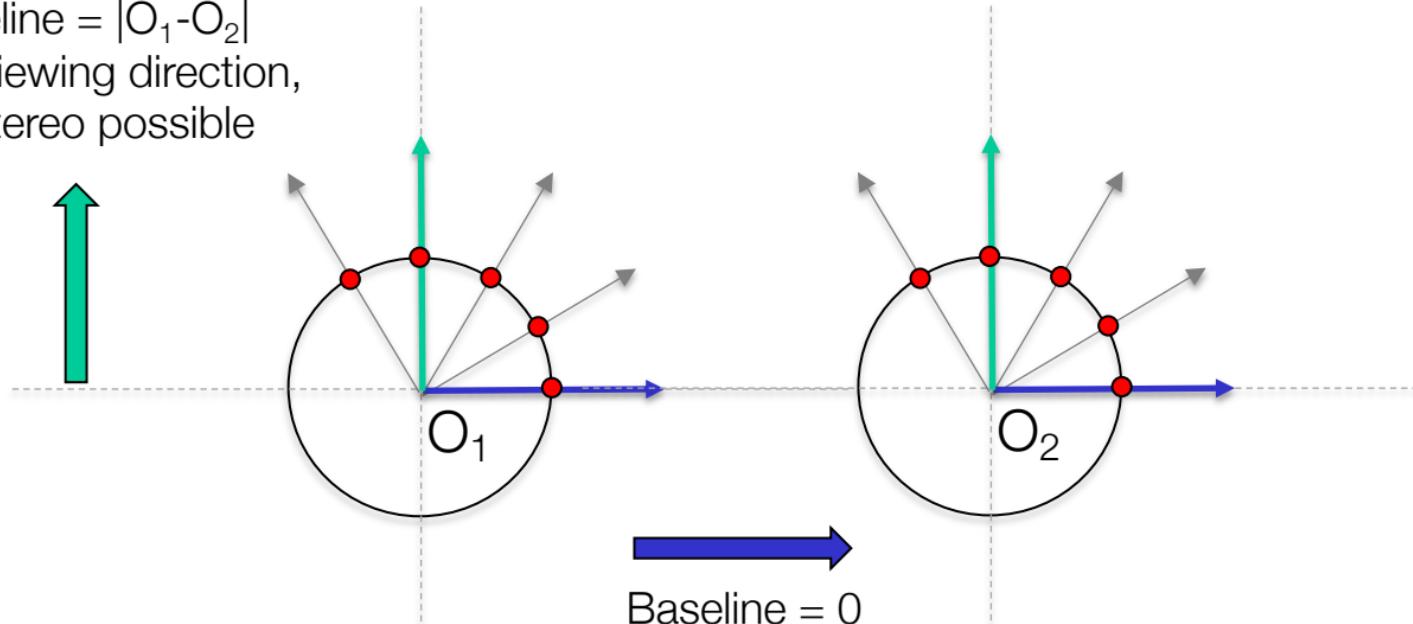
- ◆ projections are to a sphere instead of a cylinder
- ◆ can't store as rectangular image without extreme stretching

Panoramas

- see CS 178 and EE 368 course material for more detail
- now common in every image processing software and cellphone

A Pair of Mono Panoramas

Baseline = $|O_1 - O_2|$
in this viewing direction,
i.e., stereo possible



Baseline = 0
in this viewing direction,
i.e., no stereo

Head Rotation

slide by Hari Lakshman (EE 368)

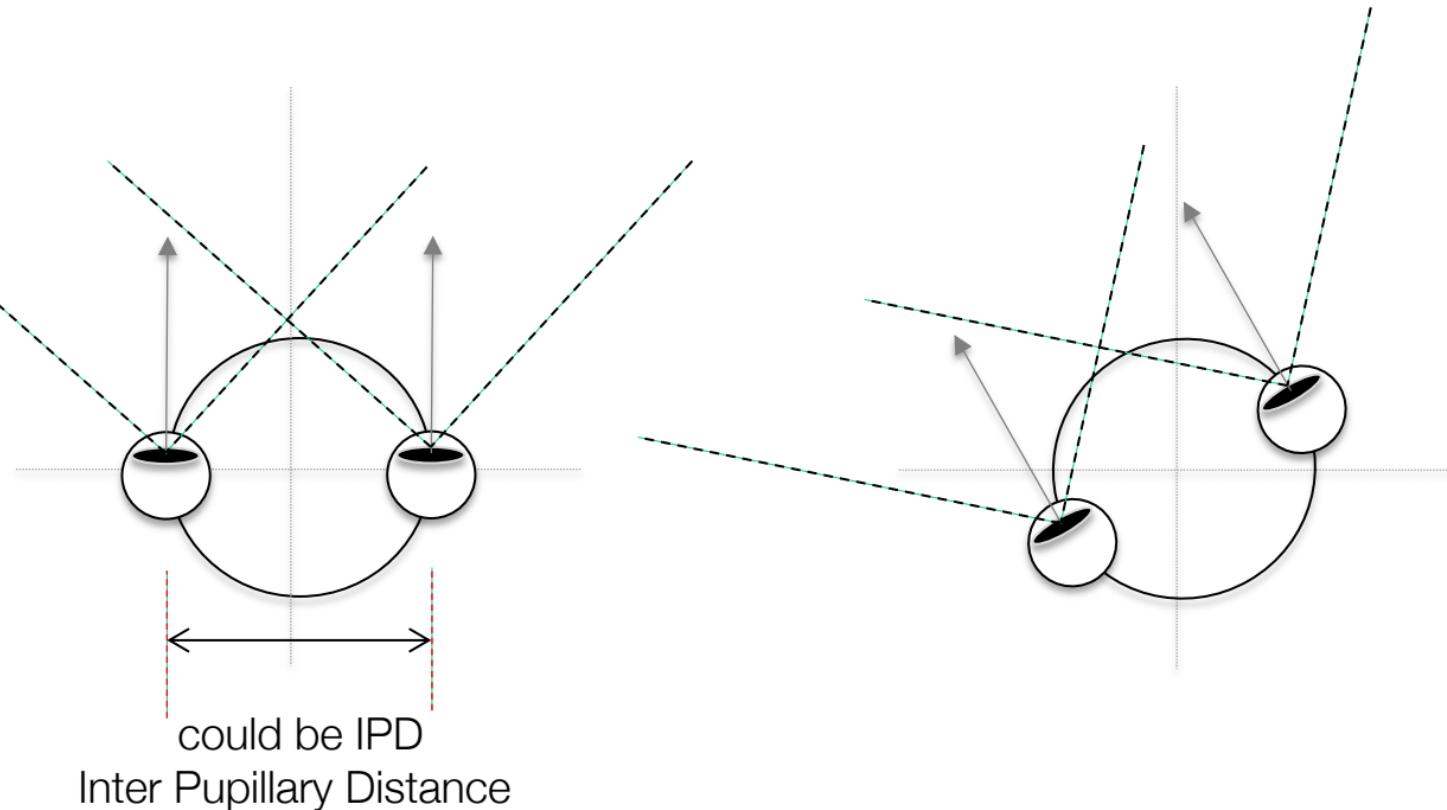
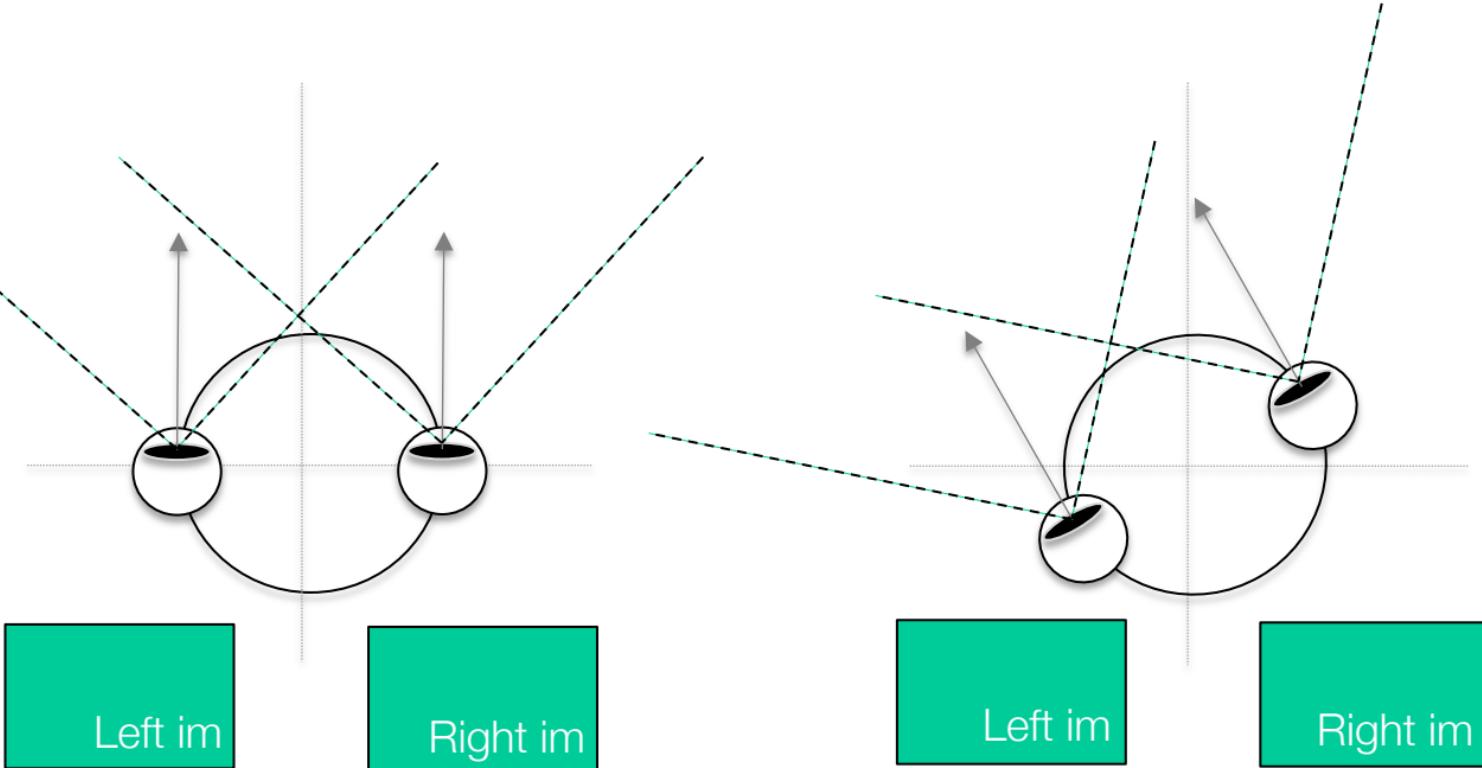
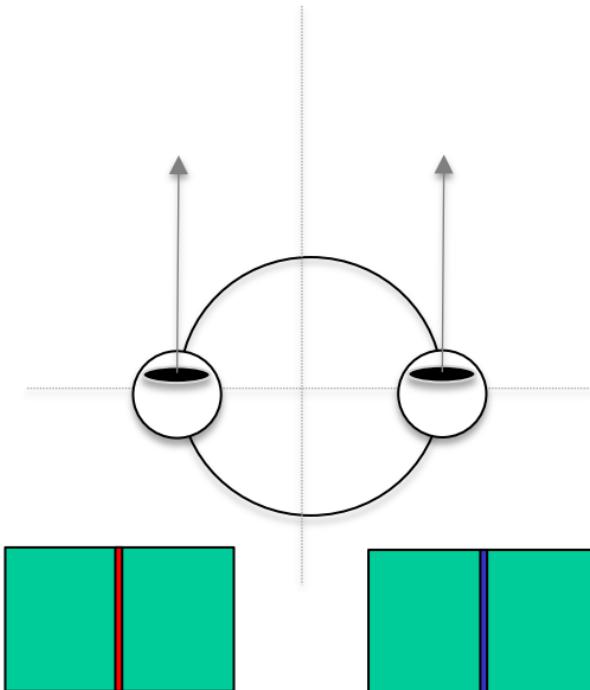


Image Pair for Each Direction

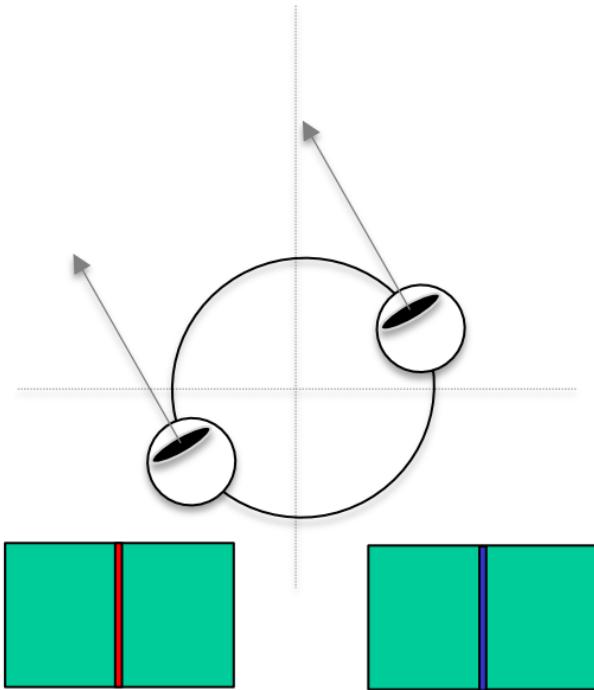


Store image pair for each direction → Problem: Too much data

Approximation: Store only Middle Ray

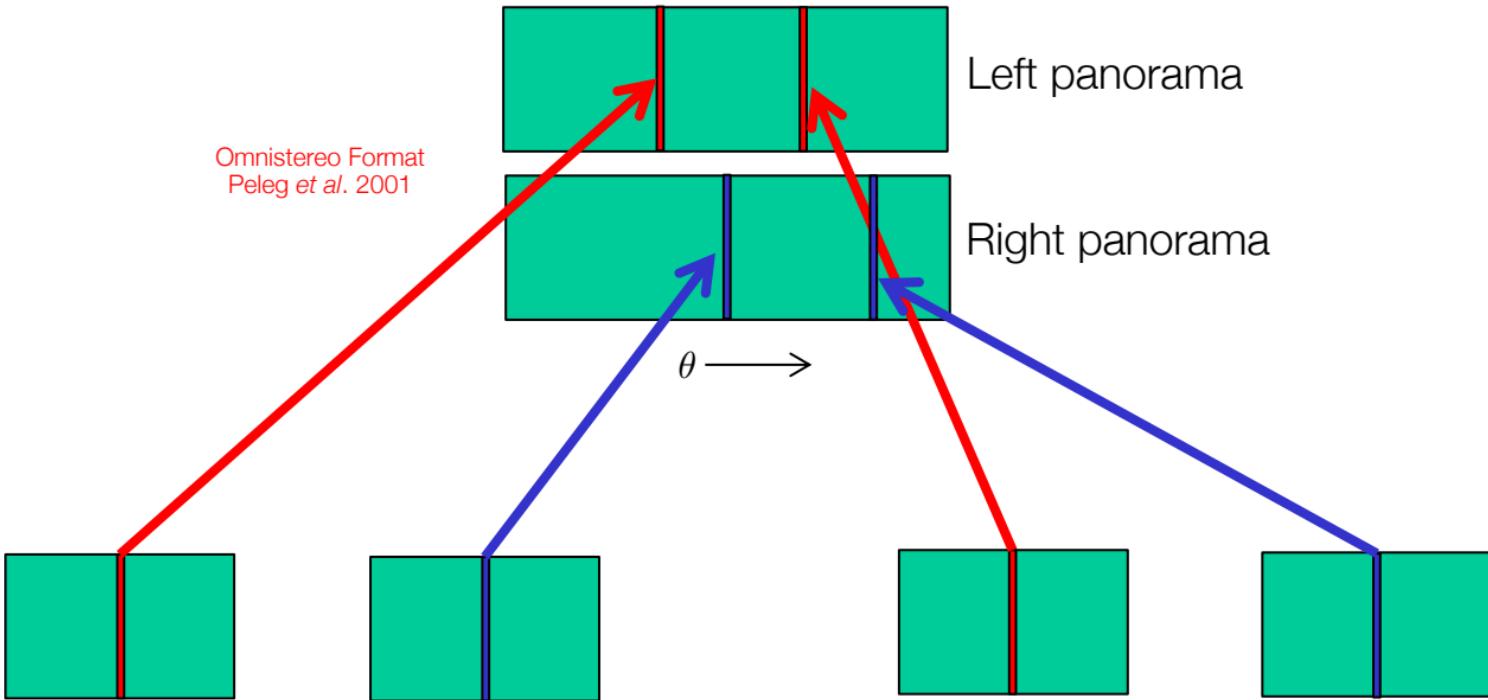


Omnistereo Format
Peleg et al. 2001

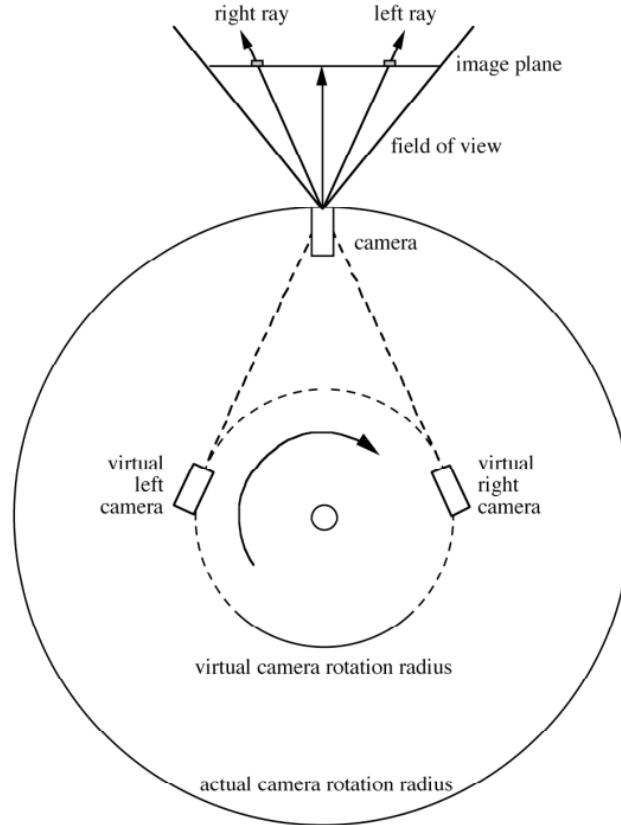


Approximation: store only middle ray for L and R eyes for each direction

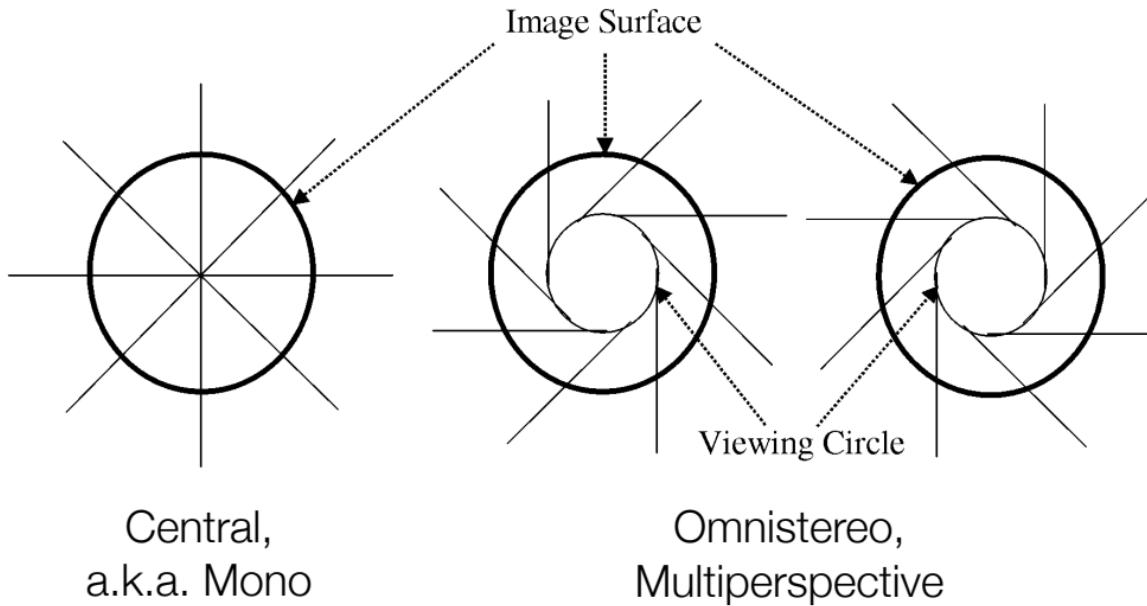
Omnistereo Panoramas



Capture using Single Camera

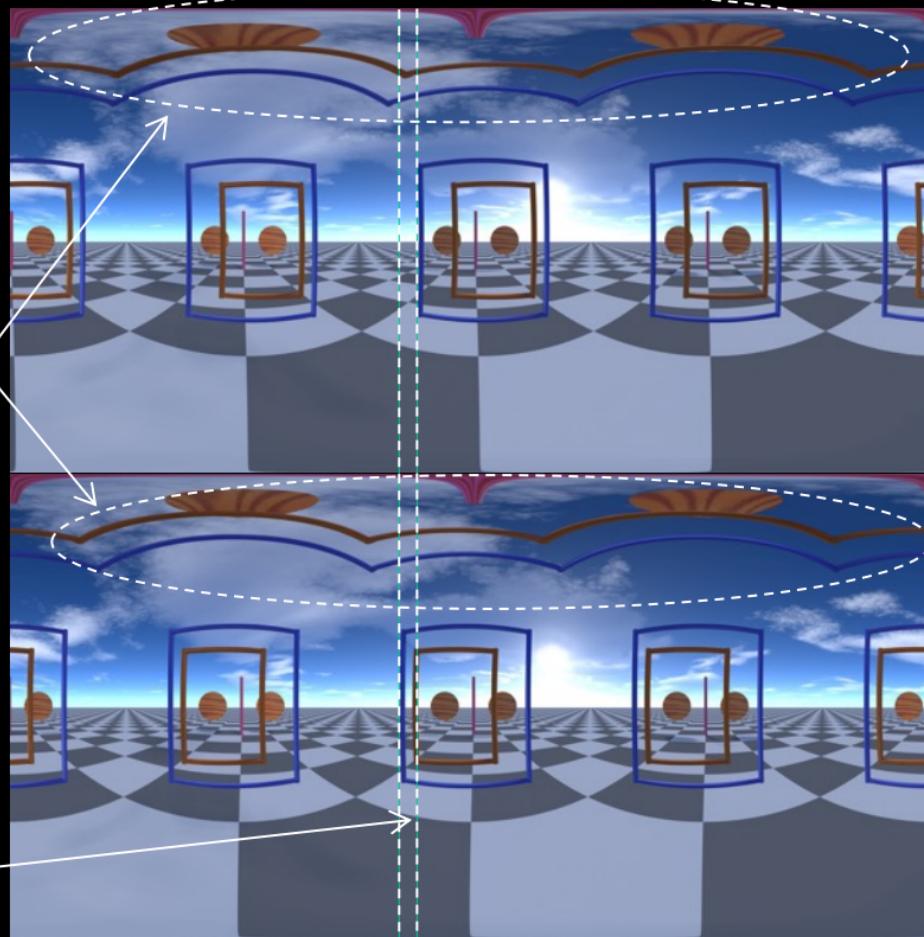


Comparison: Mono and Stereo Panoramas



Omnistereo example

slide by Hari Lakshman (EE 368)



Left panorama

Sphere-to-plane
distortions

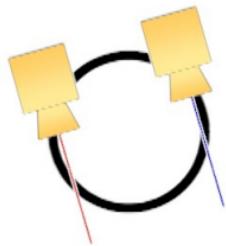
Right panorama

Disparity

Multiperspective Projection



Omnidirectional Stereo



Left Eye



Right Eye



widely used by YouTube VR, Google Daydream, Facebook, ...

Existing VR Cameras

Recorded Videos ~ 17 Gb/sec



Facebook's Surround 360



RAW Data: 17 Gb/sec

Compute time: days to weeks on conventional computer,
minutes to hours on data center

Facebook's Surround 360



RAW Data: 17 Gb/sec

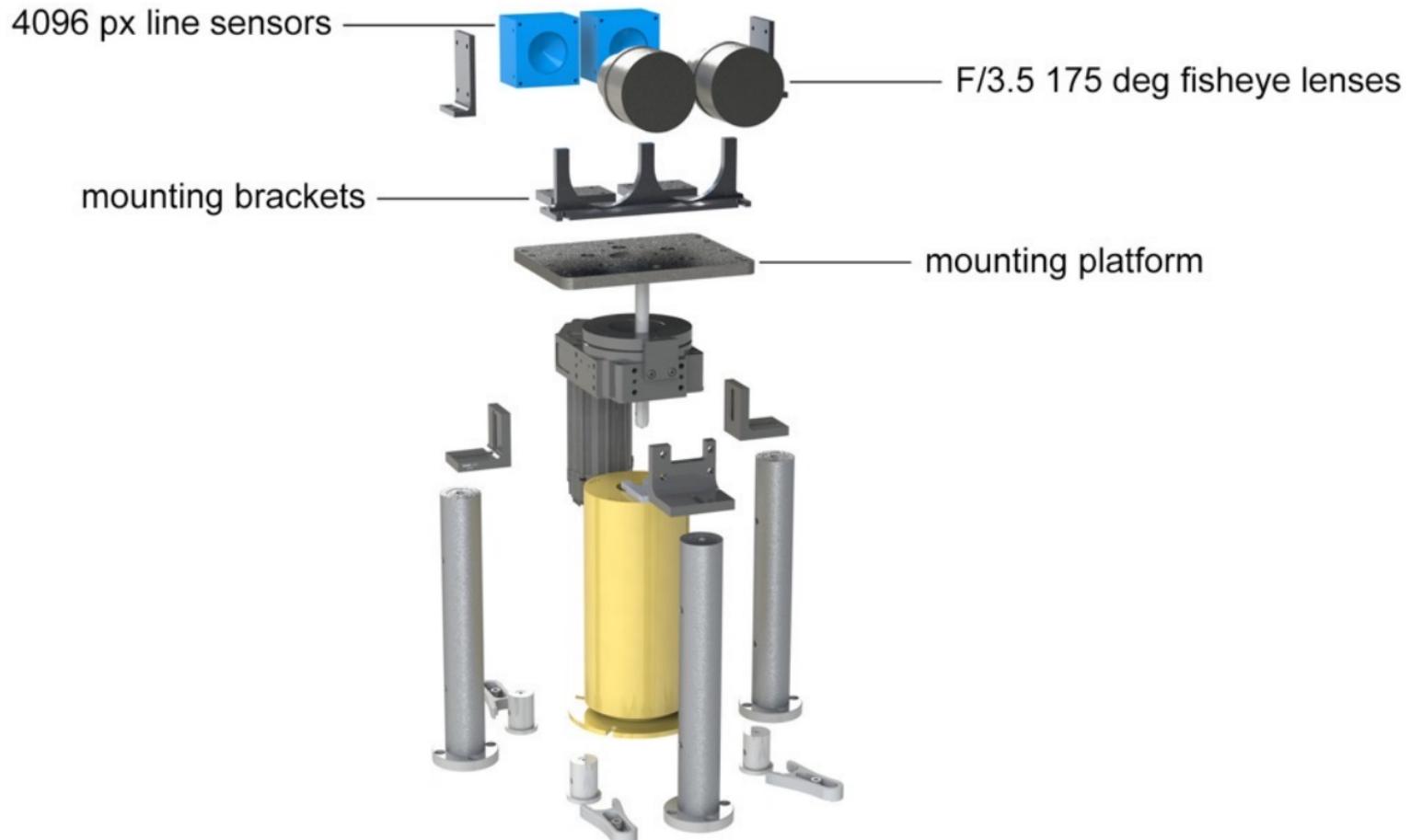
Compute time: days to weeks on conventional computer,
minutes to hours on data center

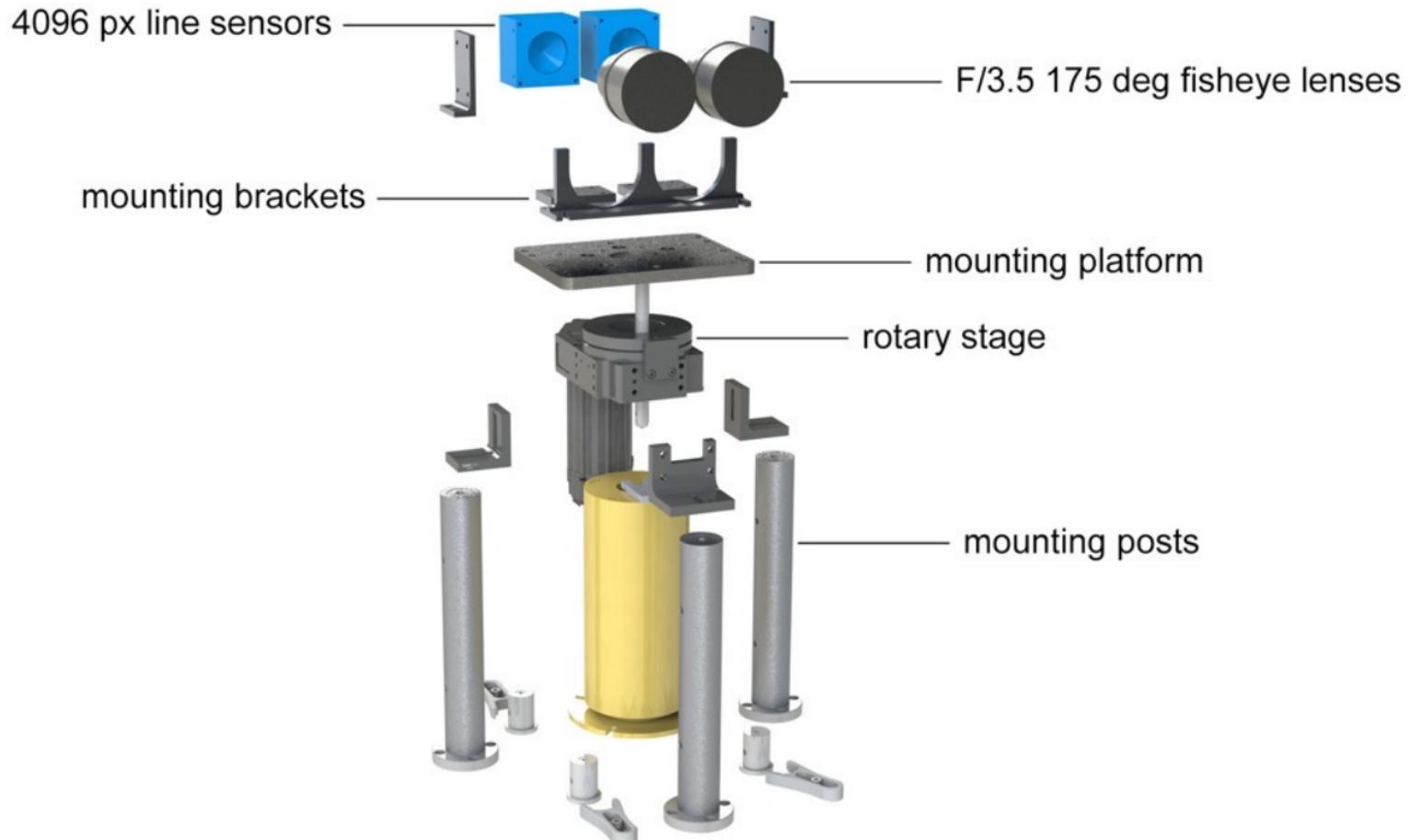


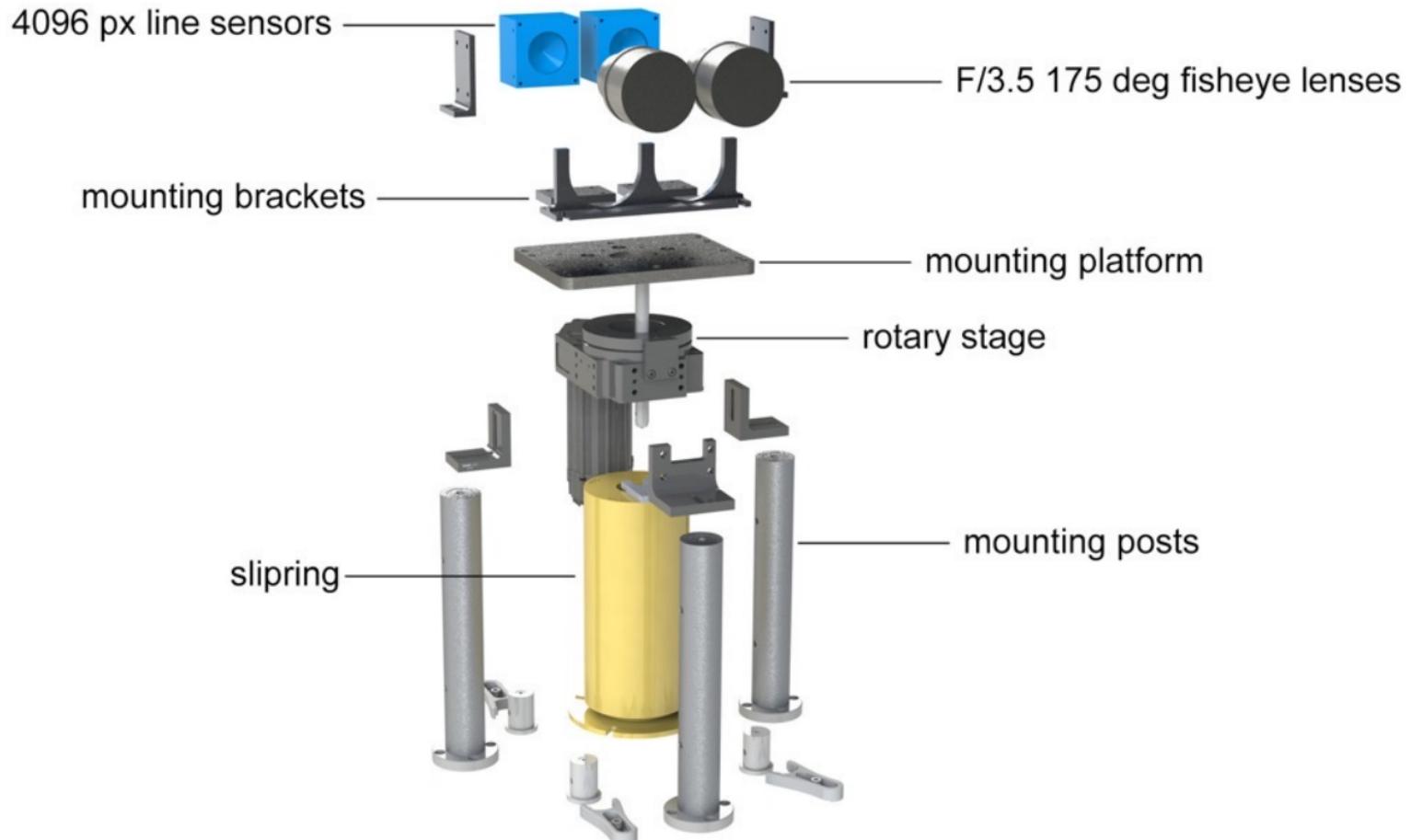
4096 px line sensors



F/3.5 175 deg fisheye lenses







Fountain15 fullres injected - YouTube

Secure https://www.youtube.com/watch?v=LrWMdQdN_to

reddit: this front pa... Facebook Yahoo! Sports Fan... NHL.com - The Nati... Research Sivo - Better Man T... Simple Science Film... Bookmarks C++/OpenGL/SOL... 287 https://perceptu... eyetracking Prevalence of refra... Other Bookmarks

YouTube Search

Up next Autoplay

PalmLane injected Anonymous Submission / views NEW 0:30

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Redneck Inventions [funny, humor, try not to laugh, lol, roflmao] My-family-and-I Recommended for you 12:24

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Fountain15 fullres injected

Anonymous Submission Channel settings

20 views Add to Share More

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COMMENTS

Konrad et al., SIGGRAPH Asia 2017 public comment...

Introduction to Spatial Sound

Overview

- what is sound? how do we synthesize it?
- the human auditory system
- stereophonic sound
- spatial audio of point sound sources
- surround sound
- ambisonics

What is Sound?

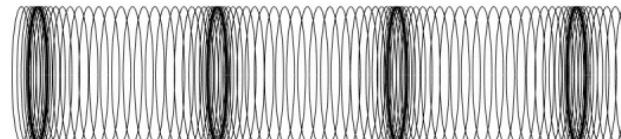
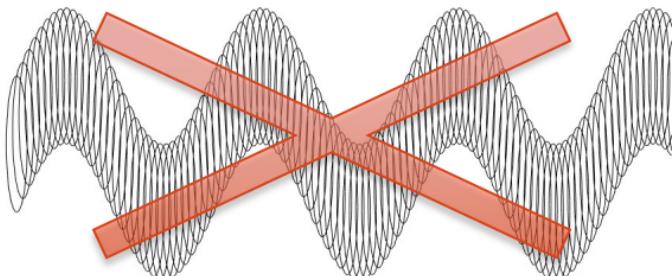
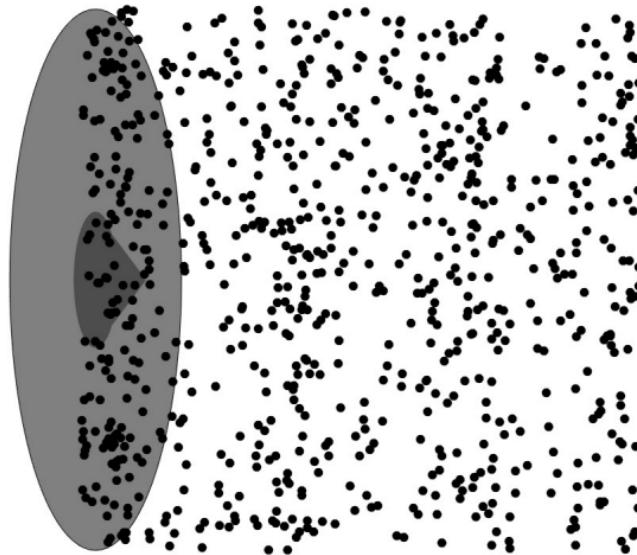
- “sound” is a pressure wave propagating in a medium
- speed of sound is $c = \sqrt{K/\rho}$ where c is velocity, ρ is density of medium and K is elastic bulk modulus
- in air, speed of sound is 340 m/s
- in water, speed of sound is 1,483 m/s

How do we Synthesize Sound?

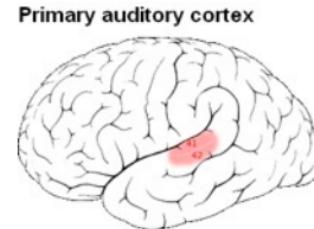
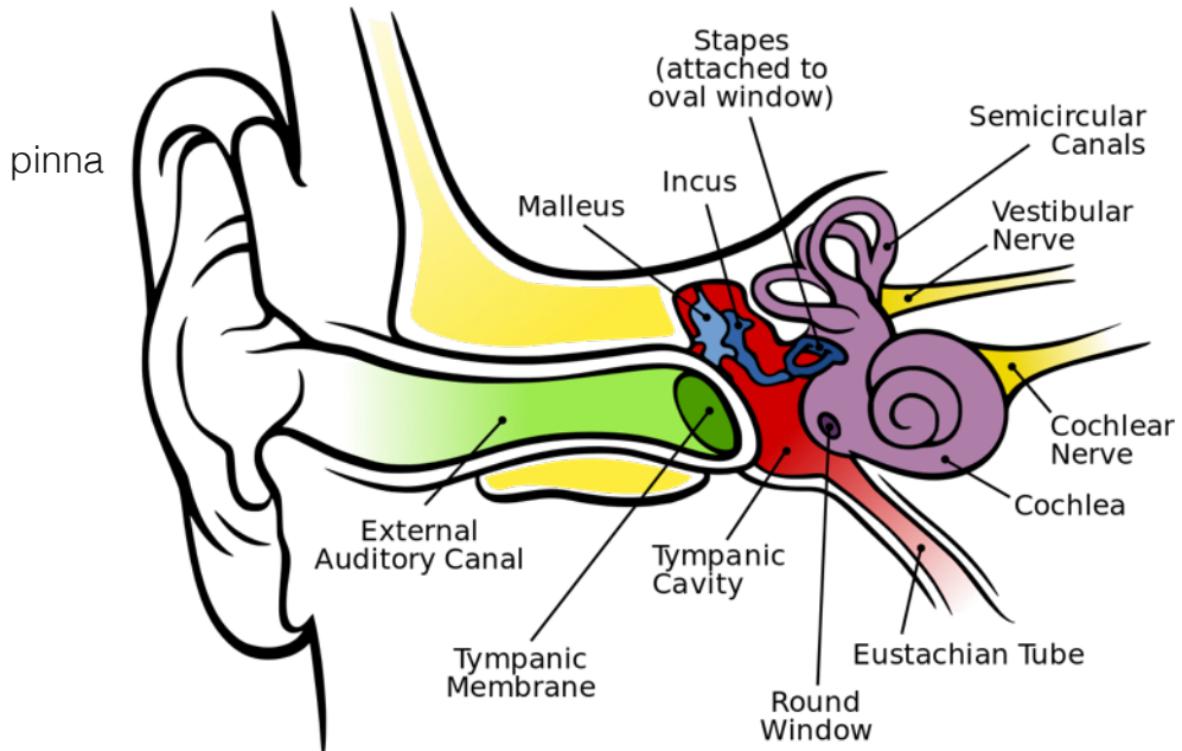


Producing Sound

- Sound is longitudinal vibration of air particles
- Speakers create wavefronts by physically compressing the air, much like one could a slinky

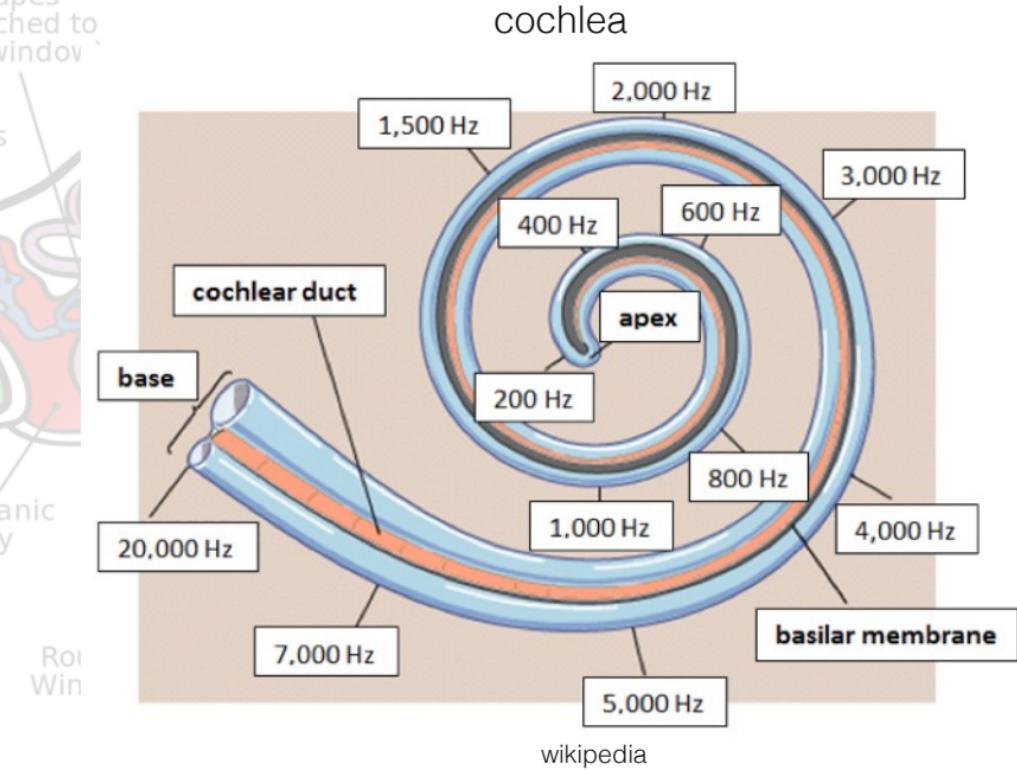
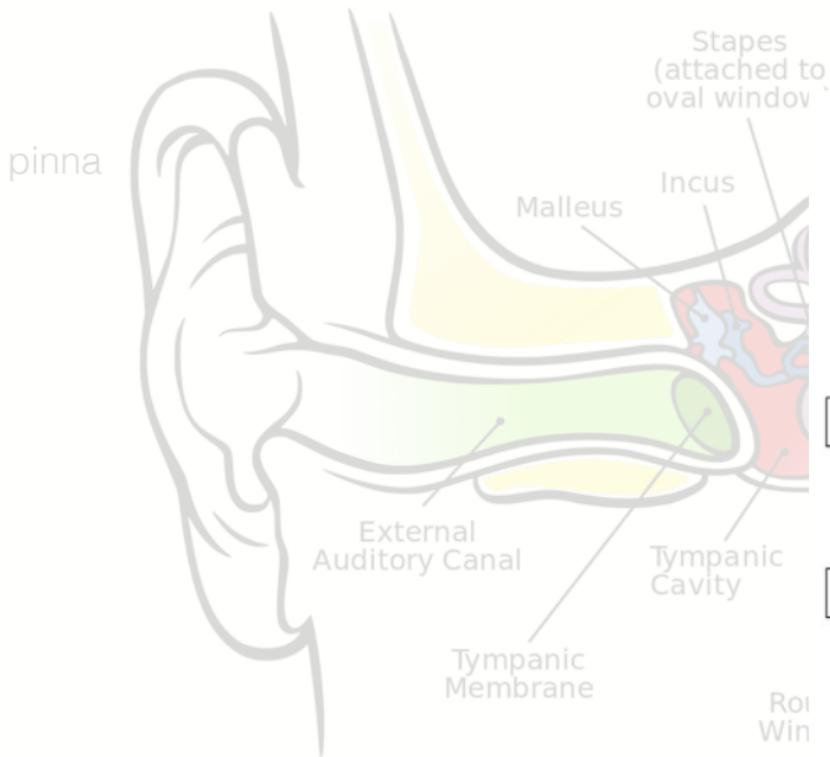


The Human Auditory System



The Human Auditory System

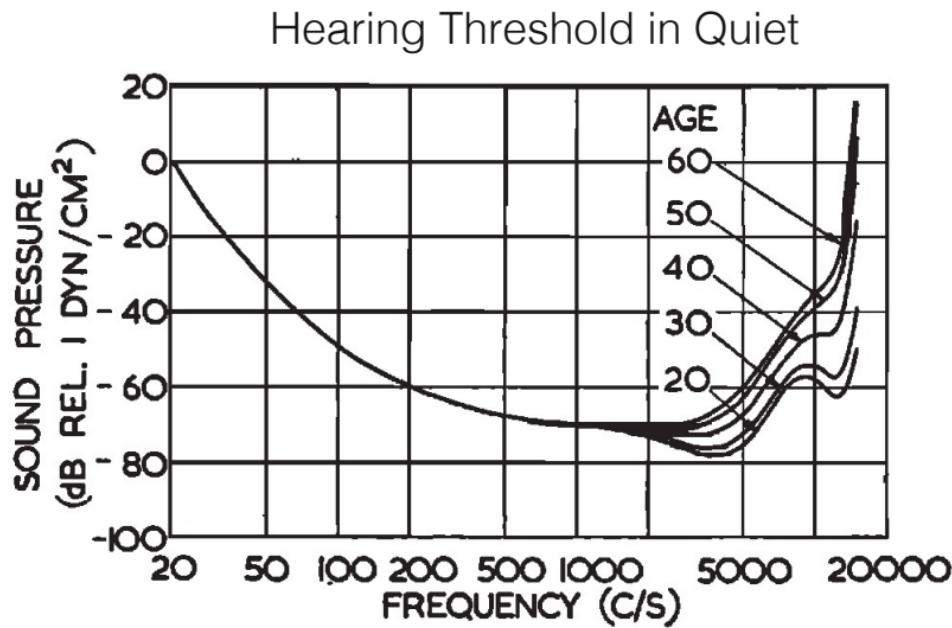
- hair receptor cells pick up vibrations



wikipedia

The Human Auditory System

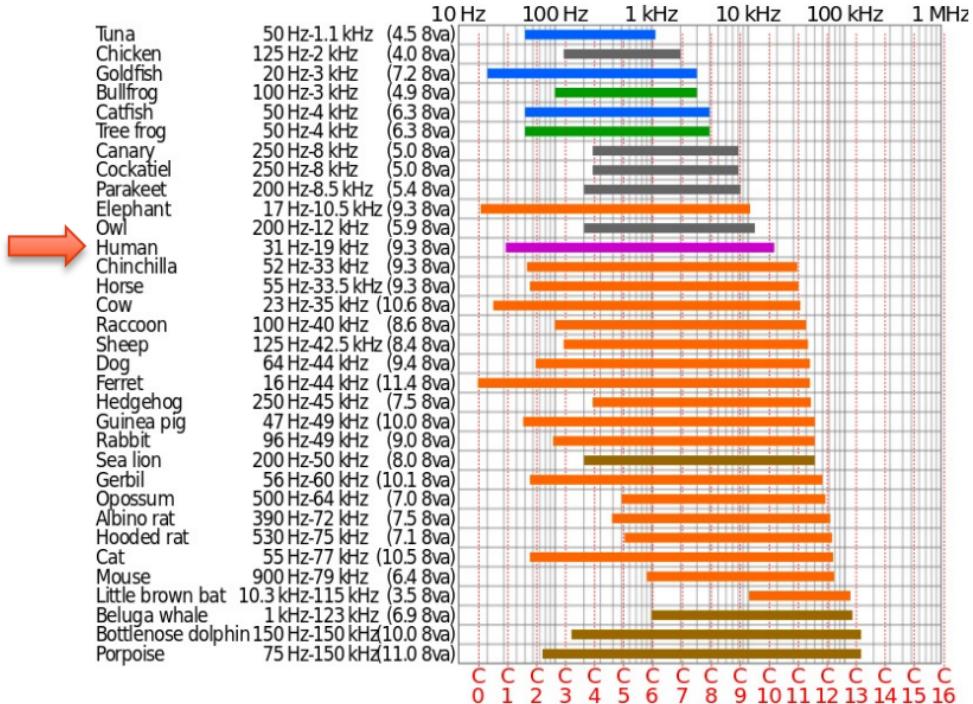
- Human hearing range:
~20–20,000 Hz
- Variation between individuals
- Degrades with age



D. W. Robinson and R. S. Dadson, 1957

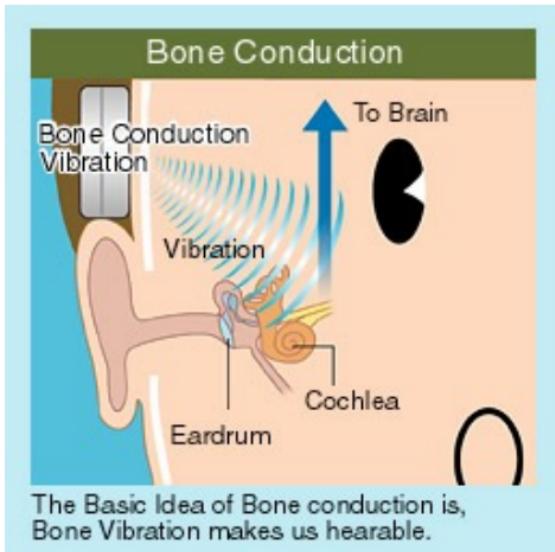
The Human Auditory System

- human hearing range:
~20 – 20,000 Hz
- variation between individuals and changes with age



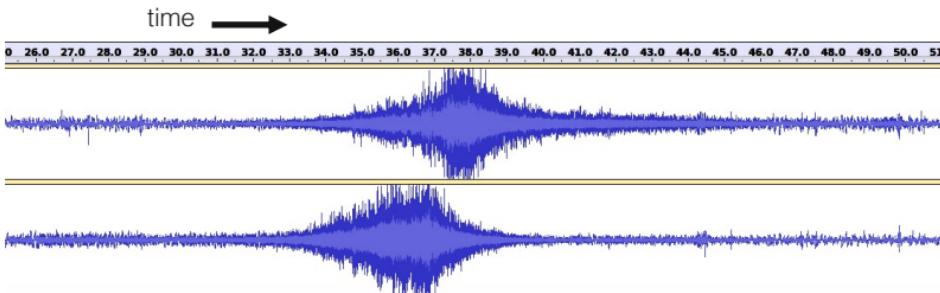
Bone Conduction

- can stimulate eardrum mechanically to create the illusion of audio, e.g. with bone conduction

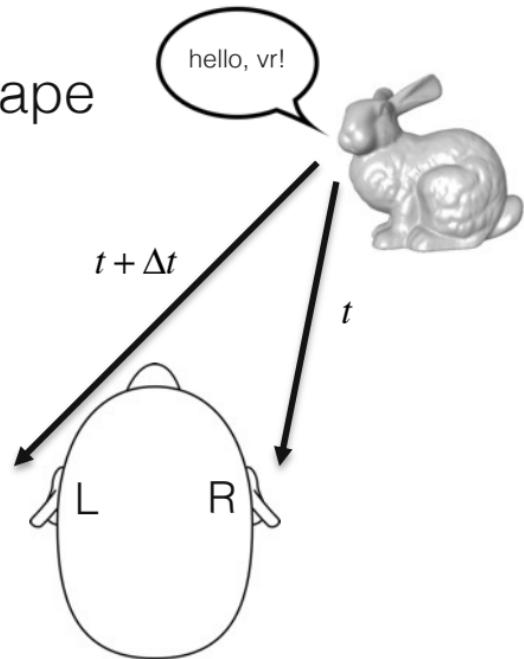


Stereophonic Sound

- mainly captures differences between the ears:
 - interaural time difference
 - amplitude differences from body shape (nose, head, neck, shoulders, ...)

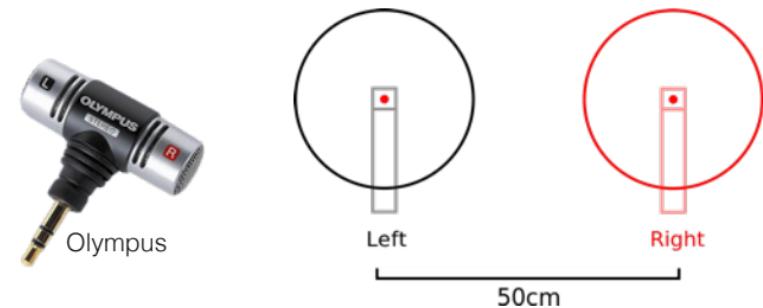


wikipedia



Stereophonic Sound Recording

- use two microphones
- A-B techniques captures differences in time-of-arrival

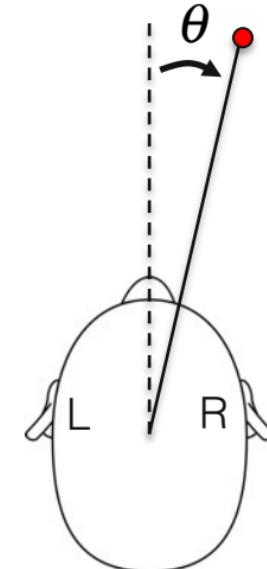


- other configurations work too, capture differences in amplitude



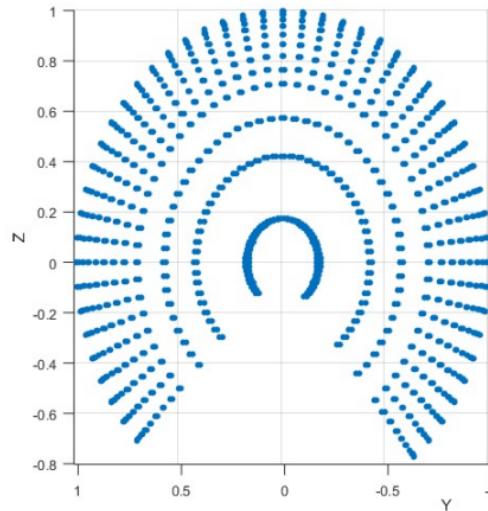
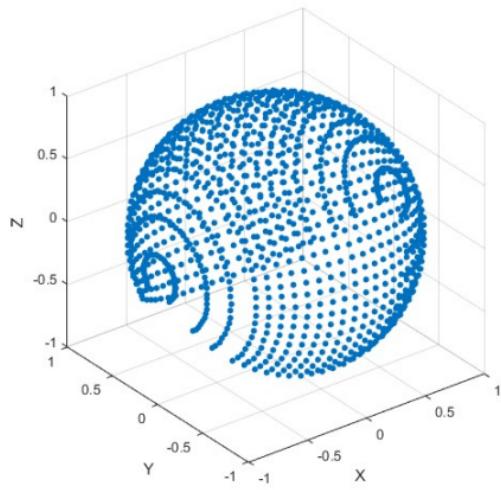
Head-related Impulse Response (HRIR)

- models phase and amplitude differences for all possible sound directions parameterized by azimuth θ and elevation ϕ
- can be measured with two microphones in ears of mannequin & speakers all around



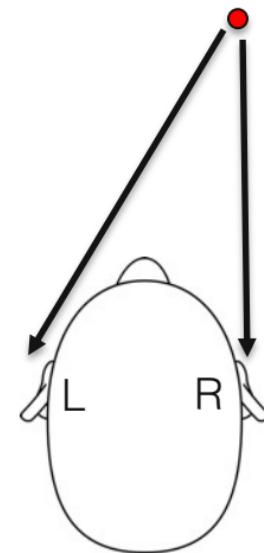
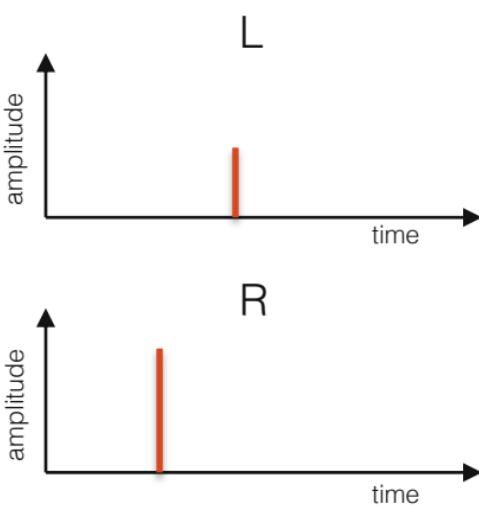
Head-related Impulse Response (HRIR)

- CIPIC HRTF database: <http://interface.cipic.ucdavis.edu/sound/hrtf.html>
- elevation: -45° to 230.625° , azimuth: -80° to 80°
- need to interpolate between discretely sampled directions



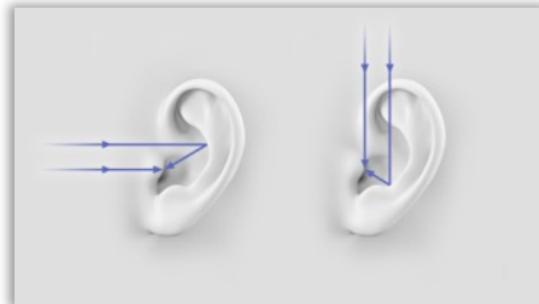
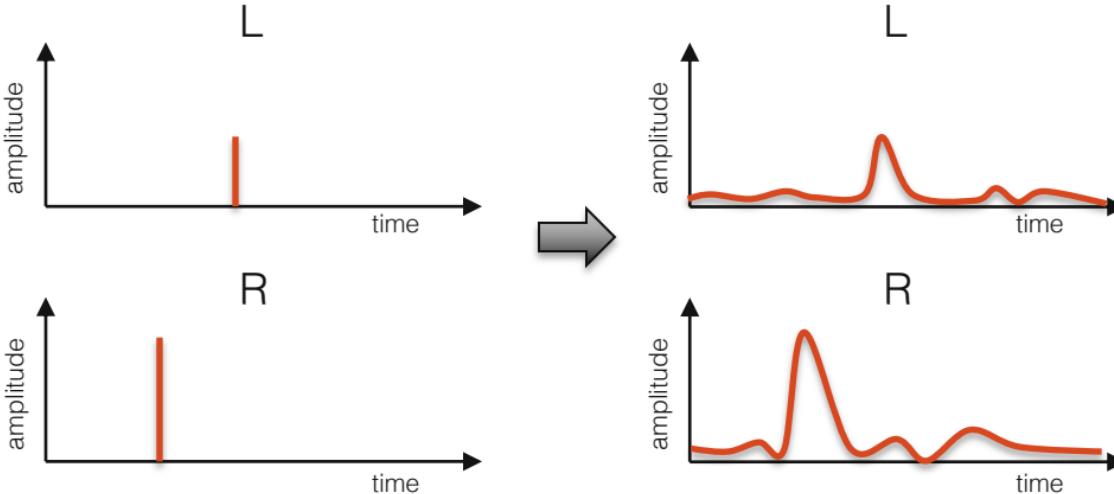
Head-related Impulse Response (HRIR)

- measuring the HRIR
 - ideal case: scaled & shifted Dirac peaks



Head-related Impulse Response (HRIR)

- measuring the HRIR
 - ideal case: scaled & shifted Dirac peaks
 - in practice: more complicated, includes scattering in the ear, shoulders etc.



Head-related Impulse Response (HRIR)

- measuring the HRIR
 - need one temporally-varying function for each angle
 - total of $2 \cdot N_\theta \cdot N_\phi \cdot N_t$ samples, where $N_{\theta,\phi,t}$ is the number of samples for azimuth, elevation, and time, respectively

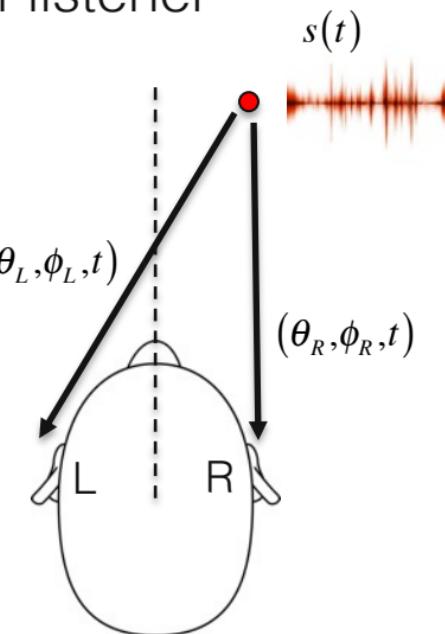
$$\text{hrir_l}(\theta, \phi, t)$$

$$\text{hrir_r}(\theta, \phi, t)$$

Head-related Impulse Response (HRIR)

applying the HRIR:

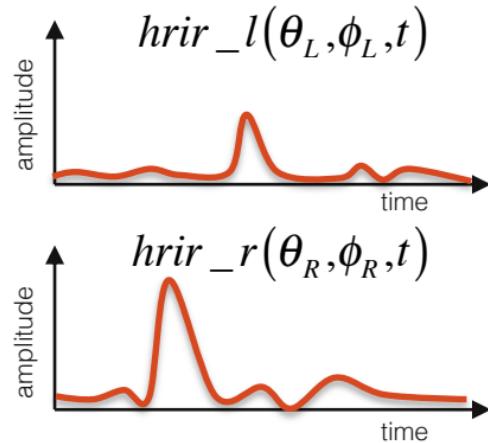
- given a mono sound source $s(t)$ and it's 3D position
1. compute (θ_L, ϕ_L) and (θ_R, ϕ_R) relative to center of listener



Head-related Impulse Response (HRIR)

applying the HRIR:

- given a mono sound source $s(t)$ and it's 3D position
1. compute (θ_L, ϕ_L) and (θ_R, ϕ_R) relative to center of listener
 2. look up measured HRIR for left and right ear at these angles



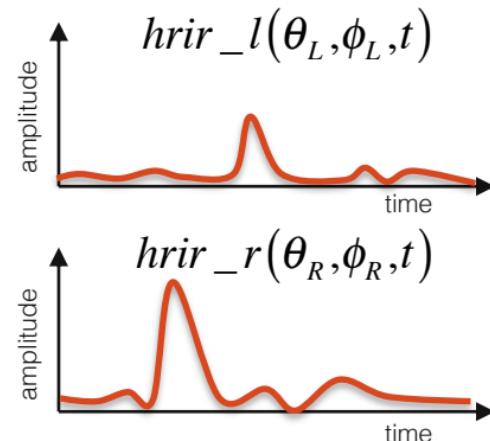
Head-related Impulse Response (HRIR)

applying the HRIR:

- given a mono sound source $s(t)$ and it's 3D position
- 1. compute (θ_L, ϕ_L) and (θ_R, ϕ_R) relative to center of listener
- 2. look up measured HRIR for left and right ear at these angles
- 3. convolve signal with HRIRs to get response for each ear as

$$s_L(t) = hrir_l(\theta_L, \phi_L, t) * s(t)$$

$$s_R(t) = hrir_r(\theta_R, \phi_R, t) * s(t)$$



Head-related Transfer Function (HRTF)

- HRTF is Fourier transform of HRIR! (you'll find the term HRTF more often than HRIR)

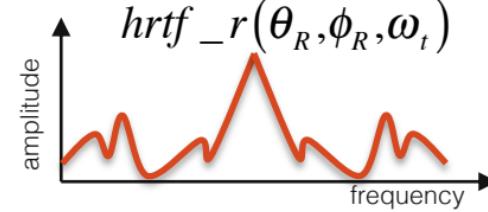
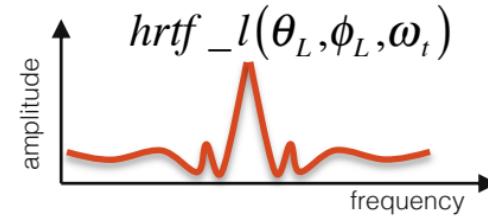
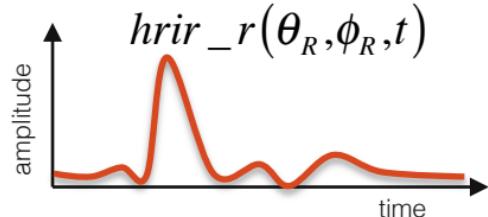
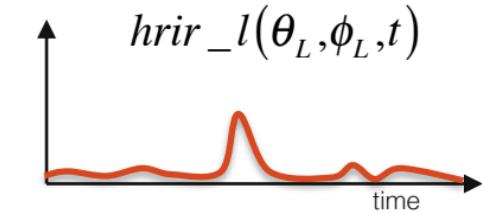
$$s_L(t) = \text{hrir_l}(\theta_L, \phi_L, t) * s(t)$$

$$s_R(t) = \text{hrir_r}(\theta_R, \phi_R, t) * s(t)$$



$$s_L(t) = F^{-1} \left\{ \text{hrtf_l}(\theta_L, \phi_L, \omega_t) \cdot F \{ s(t) \} \right\}$$

$$s_R(t) = F^{-1} \left\{ \text{hrtf_r}(\theta_R, \phi_R, \omega_t) \cdot F \{ s(t) \} \right\}$$



Head-related Transfer Function (HRTF)

- HRTF is Fourier transform of HRIR! (you'll find the term HRTF more often than HRIR)

$$s_L(t) = \text{hrir_l}(\theta_L, \phi_L, t) * s(t)$$

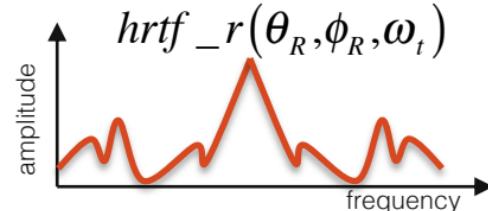
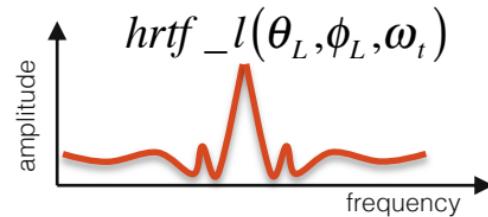
$$s_R(t) = \text{hrir_r}(\theta_R, \phi_R, t) * s(t)$$



$$s_L(t) = F^{-1} \left\{ hrtf_l(\theta_L, \phi_L, \omega_t) \cdot F\{s(t)\} \right\}$$

$$s_R(t) = F^{-1} \left\{ hrtf_r(\theta_R, \phi_R, \omega_t) \cdot F\{s(t)\} \right\}$$

convolution theorem



Head-related Transfer Function (HRTF)

- HRTF is Fourier transform of HRIR! (you'll find the term HRTF more often than HRIR)

$$s_L(t) = \text{hrir_l}(\theta_L, \phi_L, t) * s(t)$$

$$s_R(t) = \text{hrir_r}(\theta_R, \phi_R, t) * s(t)$$



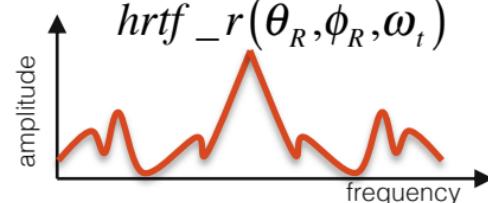
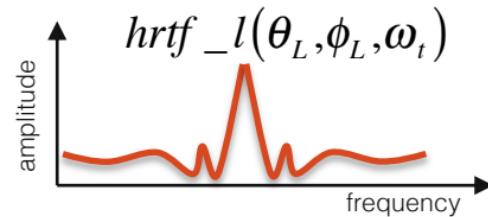
$$s_L(t) = F^{-1} \left\{ hrtf_l(\theta_L, \phi_L, \omega_t) \cdot F\{s(t)\} \right\}$$

$$s_R(t) = F^{-1} \left\{ hrtf_r(\theta_R, \phi_R, \omega_t) \cdot F\{s(t)\} \right\}$$

- properties of HRTF:

- complex-valued

- symmetric (because HRIR is real-valued)



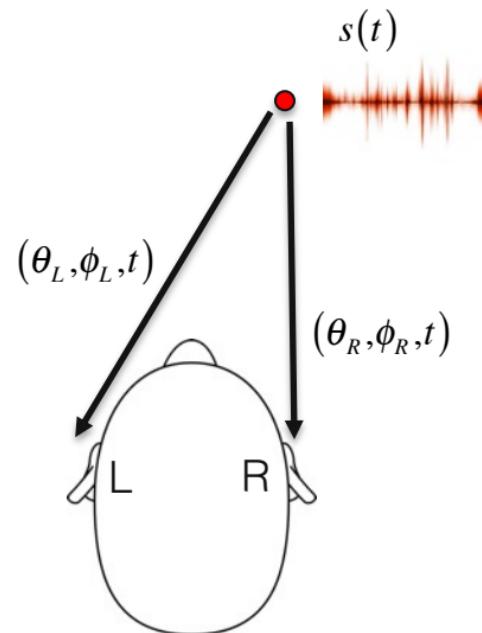
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$$s_L(t) = F^{-1} \left\{ hrtf_l(\theta_L, \phi_L, \omega_t) \cdot F\{s(t)\} \right\}$$

$$s_R(t) = F^{-1} \left\{ hrtf_r(\theta_R, \phi_R, \omega_t) \cdot F\{s(t)\} \right\}$$

Spatial Sound of 1 Point Sound Source

- given $s(t)$ and 3D position, follow instructions from last slides by convolving Fourier transform of s with HRTFs for each ear

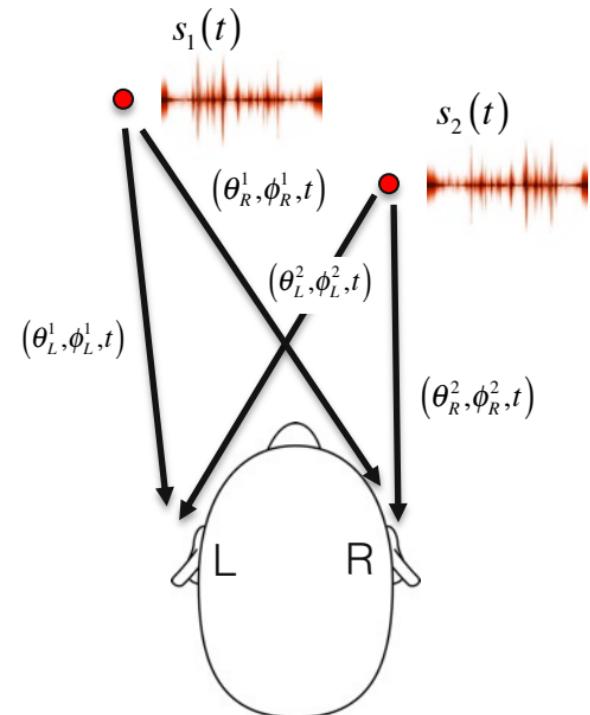


Spatial Sound of N Point Sound Sources

- superposition principle holds, so just sum the contributions of each

$$s_L(t) = \sum_{i=1}^N F^{-1} \left\{ hrtf - l(\theta_L^i, \phi_L^i, \omega_t) \cdot F\{s_i(t)\} \right\}$$

$$s_R(t) = \sum_{i=1}^N F^{-1} \left\{ hrtf - r(\theta_R^i, \phi_R^i, \omega_t) \cdot F\{s_i(t)\} \right\}$$



Surround Sound

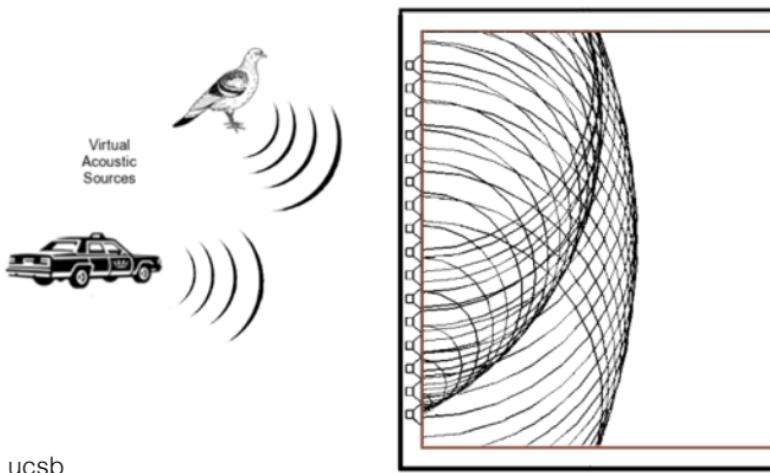
- approximate continuous wave field with discrete set of speakers



- most common:
5.1 surround sound =
5 (channels) . 1 (bass)
→ 6 channels total

Surround Sound

- approximate continuous wave field with discrete set of speakers
- can also use more speakers for “wave field synthesis” (i.e. audio hologram)



<http://spatialaudio.net/>

Surround Sound

- approximate continuous wave field with discrete set of speakers
- can also use more speakers for “wave field synthesis” (i.e. audio hologram)
- for wave field synthesis, phase of speakers needs to be synchronized, i.e. a phased array!

Surround Sound & HRTF

- for all speaker-based (surround) sound, we don't need an HRTF because the ears of the listener will apply them!
- speaker setup usually needs to be calibrated

Spatial Audio for VR

- VR/AR requires us to re-think audio, especially spatial audio!
- could use 5.1 surround sound and set up “virtual speakers” in the virtual environment – can use existing content, but not super easy to capture new content; also doesn’t capture directionality from above/below

Spatial Audio for VR

Two primary approaches:

1. Real-time sound engine

- render 3D sound sources via HRTF in real-time, just as discussed in the previous slides
- used for games and synthetic virtual environments
- a lot of libraries available: FMOD, OpenAL, ...

Spatial Audio for VR

Two primary approaches:

2. Spatial sound recorded from real environments

- most widely used format now: ambisonics
- simple microphones exist
- relatively easy mathematical model
- only need 4 channels for starters
- used in YouTube VR and many other platforms

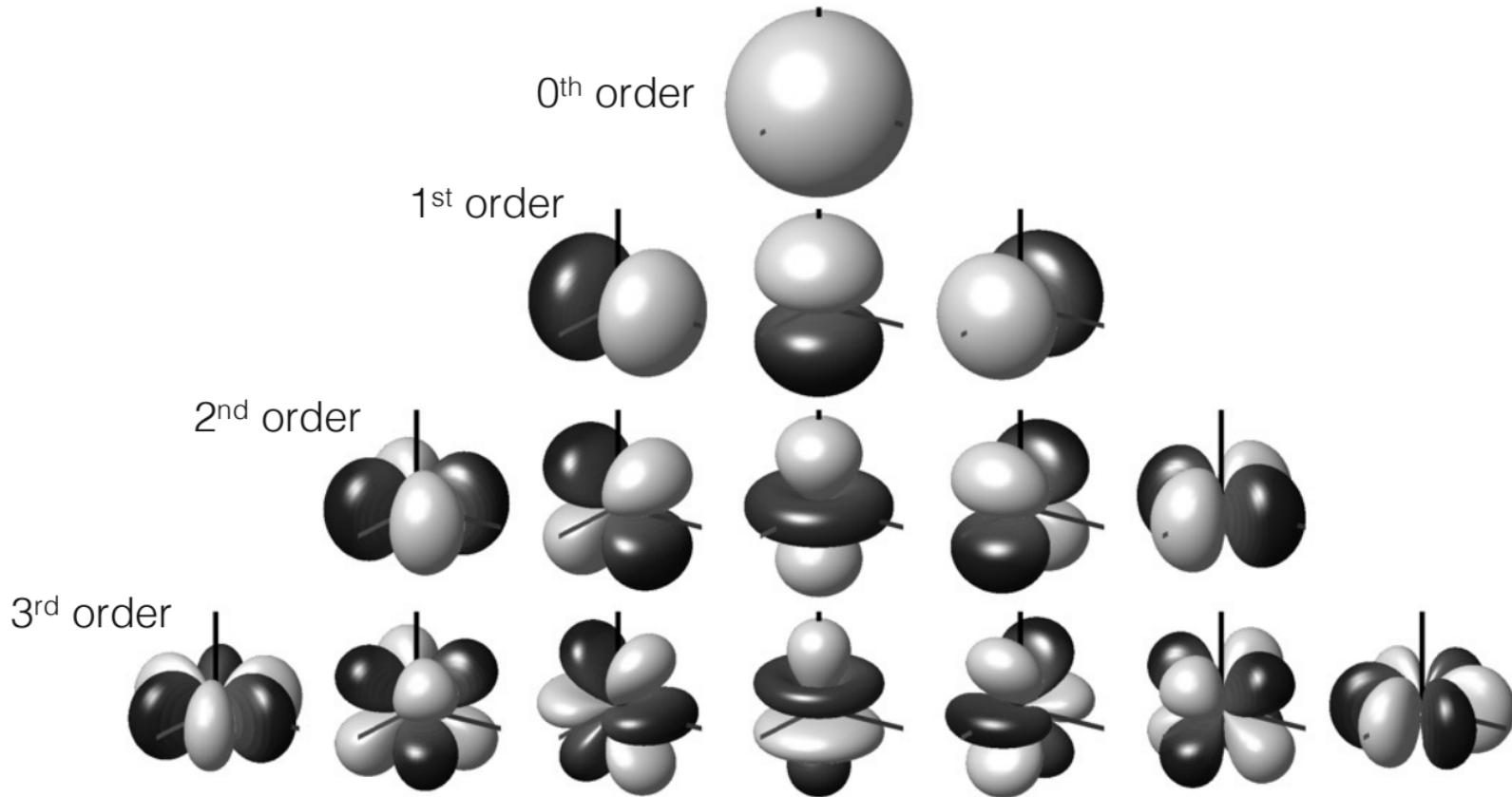
Ambisonics

- idea: represent sound incident at a point (i.e. the listener) with some directional information
- using all angles θ, ϕ is impractical – need too many sound channels (one for each direction)
- some lower-frequency (in direction) components may be sufficient → directional basis representation to the rescue!

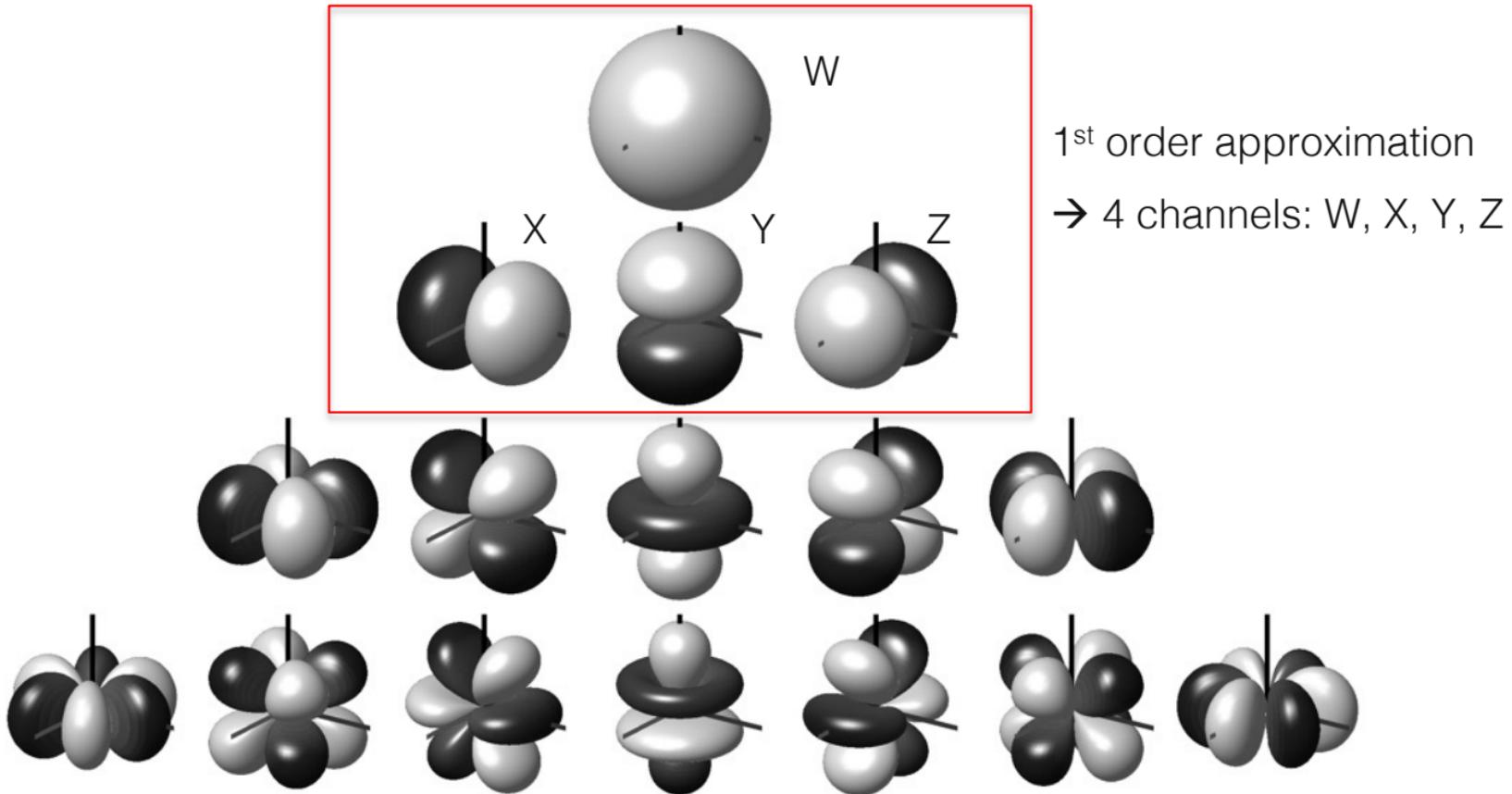
Ambisonics – Spherical Harmonics

- use spherical harmonics!
- orthogonal basis functions on a sphere, i.e. full-sphere surround sound
- think Fourier transform acting on the directions of a sphere

Ambisonics – Spherical Harmonics



Ambisonics – Spherical Harmonics



Ambisonics – Spherical Harmonics

- can easily convert a point sound source to the 4-channel ambisonics representation
- given azimuth and elevation θ, ϕ , compute W,X,Y,Z as

$$W = S \cdot \frac{1}{\sqrt{2}}$$

← omnidirectional component (angle-independent)

$$X = S \cdot \cos \theta \cos \phi$$

← “stereo in x”

$$Y = S \cdot \sin \theta \cos \phi$$

← “stereo in y”

$$Z = S \cdot \sin \phi$$

← “stereo in z”

Ambisonics – Spherical Harmonics

- can also record 4-channel ambisonics via special microphone
- same format supported by YouTube VR and other platforms



Ambisonics – Spherical Harmonics

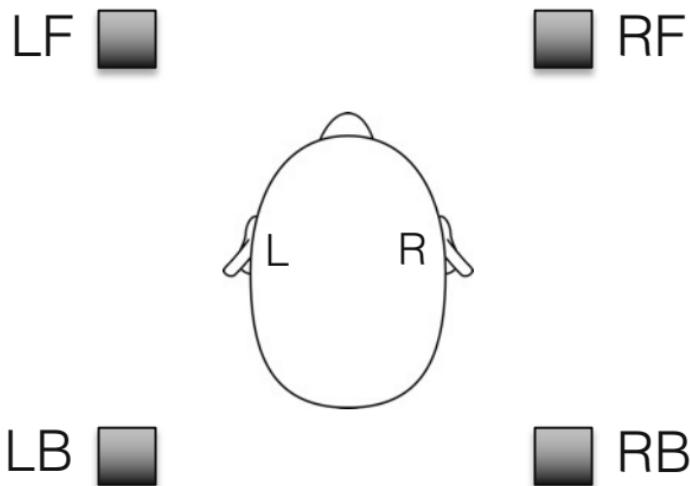
- easiest way to render ambisonics: convert W,X,Y,Z channels into 4 virtual speaker positions
- for a regularly-spaced square setup, this results in

$$LF = (2W + X + Y)\sqrt{8}$$

$$LB = (2W - X + Y)\sqrt{8}$$

$$RF = (2W + X - Y)\sqrt{8}$$

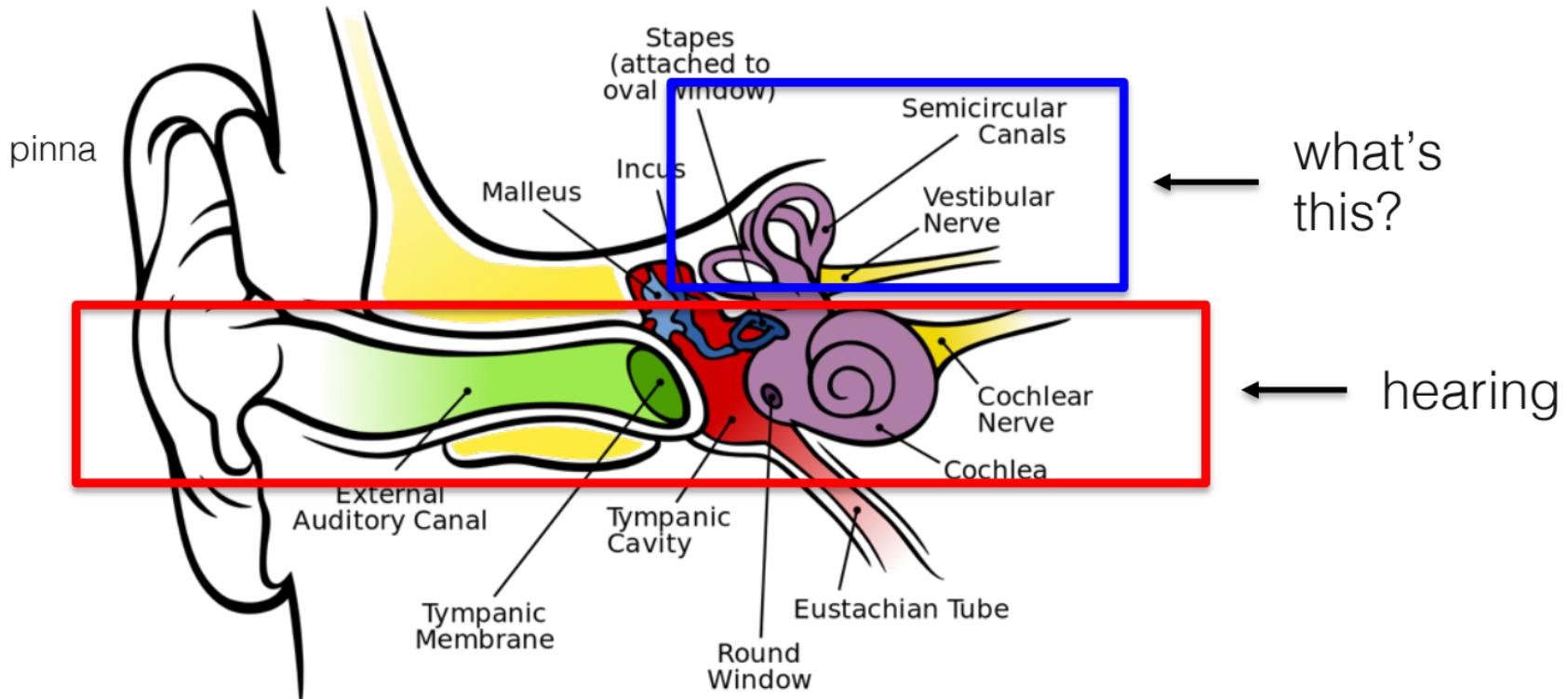
$$RB = (2W - X - Y)\sqrt{8}$$



The Vestibular System

or “What else is happening in the inner ear?”

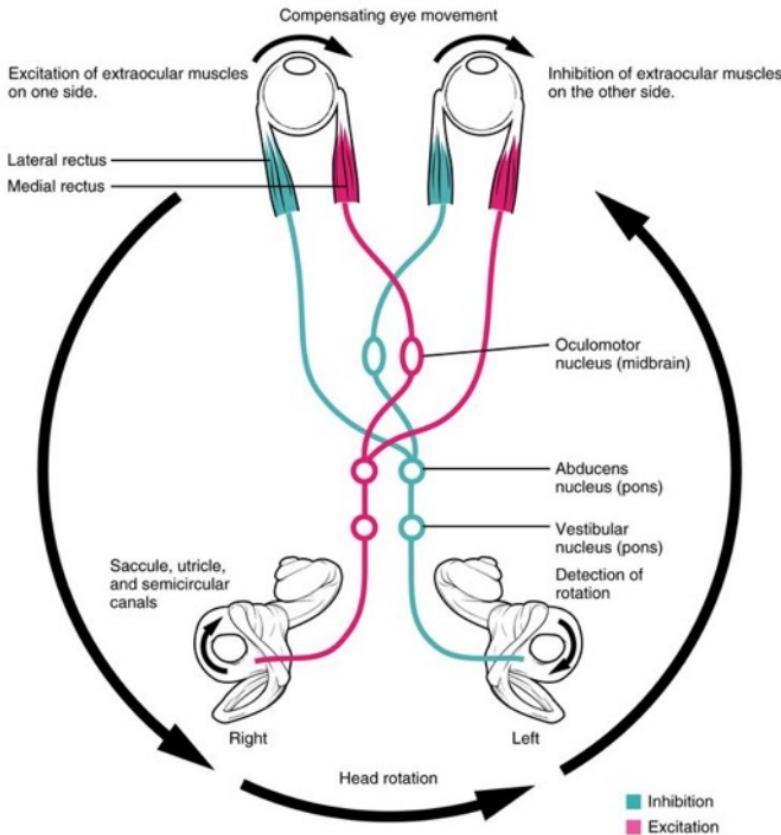
The Inner Ear



Brief Overview of the Vestibular System

- provides sense of balance & gravity
- like IMUs – one in each ear!
- in each ear, sense linear (3 dof from otolithic organs) and angular (3 dof from 3 semicircular canals) acceleration via hair cells

Vestibulo-Ocular Reflex (VOR)



- vestibular system and ocular system are directly coupled in a feedback system
- enables low-latency “optical image stabilization” of the visual system with head motion

Motion Sickness

3 types of motion sickness (all related to visual-vestibular conflict theory):

1. Motion sickness caused by motion that is felt but not seen
2. Motion sickness caused by motion that is seen but not felt
3. Motion sickness caused when both systems detect motion but they do not correspond.

Motion Sickness

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Example: car and sea sickness

Motion Sickness

3 types of motion sickness (all related to visual-vestibular conflict theory):

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3. Motion sickness caused when both systems detect motion but they do not correspond.

Example: VR sickness or visually-induced motion sickness (VIMS)

Motion Sickness

3 types of motion sickness (all related to visual-vestibular conflict theory):

1. Motion sickness caused by motion that is felt but not seen
2. Motion sickness caused by motion that is seen but not felt
3. Motion sickness caused when both systems detect motion but they do not correspond.

Example: motion in low gravity

References and Further Reading

Panoramic Imaging and VR

- M. Brown, D. Lowe “Automatic Panoramic Image Stitching using Invariant Features”, IJCV 2007
- autostitch: <http://matthewalunbrown.com/autostitch/autostitch.html>
- S. Peleg, M. Ben-Ezra, Y. Pritch “Omnistereo: Panoramic Stereo Imaging” IEEE PAMI 2001
- Konrad et al. “SpinVR: Towards Live Streaming VR Video”, ACM SIGGRAPH Asia 2017

References and Further Reading - Spatial Sound

- Google's take on spatial audio: <https://developers.google.com/vr/concepts/spatial-audio>

HRTF:

- Algazi, Duda, Thompson, Avendado "The CIPIC HRTF Database", Proc. 2001 IEEE Workshop on Applications of Signal Processing to Audio and Electroacoustics
- download CIPIC HRTF database here: <http://interface.cipic.ucdavis.edu/sound/hrtf.html>

Resources by Google:

- <https://github.com/GoogleChrome/omnitone>
- <https://developers.google.com/vr/concepts/spatial-audio>
- <https://opensource.googleblog.com/2016/07/omnitone-spatial-audio-on-web.html>
- <http://googlechrome.github.io/omnitone/#home>
- <https://github.com/google/spatial-media/>